ELASTIC RECOVERY EVALUATION OF SAUDI ASPHALT MODIFIED WITH COMMERCIAL POLYMERS

BY

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I would like to dedicate this work to my beloved family

& my Lovely Fiancé

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LIST OF ABBREVIATIONS

AASHTO : American Association of State Highway and Transportation Officials

ANOVA : Analysis of Variance

BBR : Bending Beam Rheometer

DSR : Dynamic Shear Rheometer

ER : Elastic Recovery (using Ductility bath)

Jnr : Non-recoverable compliance

MOT : Ministry of Transportation

MSCR : Multiple Stress Creep Recovery

PAV : Pressure Ageing Vessel

Pb : Polybilt

PG : Performance Grade

PMA : Polymer Modified Asphalt

RTFO : Rolling Thin Film Oven

SBS : Styrene-Butadiene-Styrene

SHRP : Strategic Highway Research Program

SPSS : Statistical Package for the Social Sciences

$\%\mathbf{R}_{3.2\,\mathrm{kPa}}$: Percent Recovery after applying 3.2 kPa repeated stress

ABSTRACT

Full Name : [Khaleel Jawad Al-Adham]

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Kingdom of Saudi Arabia has invested in a massive road network over the past thirty five years. The roads, which have been built to the best international standards, have shown early signs of distresses due to the harsh environment and traffic loading. Local asphalt pavement temperature ranges between −10 °C in the winter to 73 °C in the summer. This has led to an increased demand to modify asphalt binders to improve the performance of local asphalt binders to minimize cracking stress, which occurs at low temperatures, and permanent deformation, which occurs at high service-temperatures. Different methods have been used to upgrade the properties of asphalt binders. One of the most commonly used procedures is modification of asphalt by addition of polymers.

Use of polymers is the most convenient for asphalt modification for local contractors. In addition to the improvement of rutting and fatigue resistance of modified asphalt, it also improves the stripping resistance of asphalt concrete mixes which make it attractive to the local market. Many methods have been used for evaluation of the asphalt binders, but most of them are empirical and there is no specific and unify standard adopted by asphalt agencies and researchers.

Asphalt researchers use Superpave specification (AASHTO M320) to investigate the behavior of unmodified asphalt binders and classify them according to the performance grading system. But for the case of polymer modified asphalt binders, highway agencies tried to supplement the existing Superpave specifications with additional tests to evaluate correctly the behavior of the polymer modified asphalts. Elastic Recovery criterion is used for this purpose by many agencies worldwide. But in Saudi Arabia, Ministry of Transport still uses the conventional Superpave standards and do not include the elastic recovery criteria in the evaluation. This additional test can only predict the presence of the polymer in the asphalt binder and does not evaluate the performance.

In order to identify elastomeric polymer modified binders in terms of their fundamental properties and performance, the Multiple Stress Creep Recovery (MSCR) test (AASHTO TP 70-08) have been studied in this research and to be introduced to the local standards. Four types of elastomeric and plastomeric polymers are selected in this study that widely used in Saudi Arabia to modify the local asphalt that produced by different refineries in the Kingdom; Ras Tannura, Riyadh, Jeddah and Yanbu.

The results of this study show that, there is a good correlation between the MSCR and Superpave Performance Grading (PG) system and also with Elastic Recovery test. This leads to the conclusion that the new test can be used as a replacement of other tests that had been used in the evaluation of polymer modified asphalt binders against rutting.

ملخص الرسالة

الاسم الكامل: خليل جواد خليل الادهم

عنوان الرسالة: تقييم خاصية استعادة المرونة للاسفلت العربي المعدّل باستخدام البوليمرات التجارية

التخصص: هندسة مدنية

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لقد استثمرت المملكة العربية السعودية في شبكة الطرق الهائلة على مدى خمسة وثلاثين عاما الماضية. تلك الطرق التي تم بناؤها بأفضل المعايير الدولية، قد أظهرت مؤشرات مبكرة على الاهتراء بسبب البيئة القاسية و حركة المرور المتزايدة. تتراوح درجات الحرارة المحلية لرصفات الأسفلت ما بين 10− درجة مئوية في فصل الشتاء إلى 73 درجة مئوية في فصل الصيف. وقد أدى ذلك إلى زيادة الطلب لتعديل الإسفلت بهدف تحسين أداء الإسفلت المحلي للحد من تكسير الإجهاد، والذي يحدث في درجات حرارة منخفضة، والتخدد، والذي يحدث في ارتفاع درجات الحرارة أثاء الخدمة .وقد استخدمت أساليب مختلفة لتحسين خصائص الإسفلت العربي أحد هذه الإجراءات الأكثر شيوعا هو تعديل الأسفلت بإضافة البوليمرات.

استخدام البوليمرات هو الأكثر ملاءمة لتعديل الأسفلت بالنسبة للمقاولين المحليين .بالإضافة إلى تحسين التخدد ومقاومة اجهاد الأسفلت، كما أنه يحسن من مقاومة انفصال الاسفلت عن الحصى للخلطات الأسفلتية التي تجعلها مجدية للسوق المحلي .وقد استخدمت العديد من الأساليب لتقييم الإسفلت، ولكن معظمها تجريبية وليس هناك معيار محدد اعتمد من قبل الباحثين.

استخدم العديد من الباحثين في مجال الأسفلت مواصفات Superpave (AASHTO M320) لدراسة سلوك الإسفلت المعدل وتصنيفه وفقا لأدائه. ولكن بالنسبة للخلطات المعدلة بالبوليمر، حاولت وكالات الطرق في المنطقة تعديل المواصفات القائمة على اختبارات إضافية لتقييم صحيح لسلوك الاسفلت المعدل بالبوليمر. لهذا الغرض، يستخدم معيار استعادة المرونة من قبل العديد من المؤسسات التي تقوم بدراسة الاسفلت في جميع أنحاء العالم .ولكن في المملكة العربية السعودية، ووزارة النقل لا يزال يستخدم المعايير التقليدية ولا تشمل معايير استعادة المرونة في التقييم .هذه الاختبارات الإضافية يمكن التنبؤ فقط وجود البوليمر في الموثق الأسفلت ولا تقييم الأداء.

من أجل تحديد مواصفات الاسفلت المعدل بواسطة البوليمرات المرنة من حيث خصائصها الأساسية والأداء، لقد تم دراسة اختبار الإجهاد المتعدد واستعادة المرونة (MSCR) (AASHTO TP 70-08) في هذا البحث وللتعرف على المعايير المحلية .حيث تم اختيار أربعة أنواع من البوليمرات المرنة واللدنة في هذه الدراسة التي استخدمت على نطاق واسع في المملكة العربية السعودية لتعديل الأسفلت المحلي والتي يتم انتاجها من مصافي مختلفة في المملكة؛ وهي رأس تنورة والرياض وجدة وينبع.

نتائج هذه الدراسة اظهرت أنه هناك علاقة رياضية جيدة بين نظام الأداء (PG) و كل من اختبار الإجهاد المتعدد واستعادة المرونة (MSCR) واختبار استعادة المرونة (ER) وهذا يؤدي إلى استنتاج مفاده أن الاختبار الجديد يمكن استخدامه كبديل عن أي اختبارات أخرى واستخدامها في تقييم الاسفلت المعدل باستخدام البوليمرات.

CHAPTER 1

INTRODUCTION

1.1 Background

Kingdom of Saudi Arabia has invested in a massive road network over the past thirty five years. The roads, which have been built to the best international standards, have shown early signs of distresses due to the harsh environment and traffic loading. Local asphalt pavement's temperature ranges between (−10 °C) in the winter to (73 °C) in the summer [Al-Abdul Wahhab et al., 1994]. This has led to an increased demand to modify asphalt binders to improve the performance of local asphalt binders to minimize cracking stress, which occurs at low temperatures, and permanent deformation, which occurs at high service temperatures.

Different methods have been used to upgrade the properties of asphalt binders. One of the most commonly used procedures is modification by addition of polymers. Use of polymers is the most convenient for asphalt modification for local contractors. Several polymer brands have been used locally. In this study, common polymers include styrene-butadiene-styrene (SBS), Polybilt 101 and Honeywell™ Titan polymers (Titan 7686 and Titan 7205) were used in the improvement of the Saudi asphalt binders.

Asphalt binders were collected from all local asphalt producing refineries including Riyadh, Ras Tanura, Jeddah and Yanbu and were subjected to physical testing and Performance Grading (PG) evaluation. On the other hand, binders were modified with 2% - 6% of Titan, SBS and Polybilt 101 polymers to improve the performance grade of these asphalts to PG 70-16 and PG 82-16. Although the performance grade is dependent on the determination of viscous and elastic components of asphalt binder at the service temperature, many researchers indicated that the (PG) is not sufficient criteria to indicate rutting resistance. Several specifications have included elastic recovery of asphalt binder (AASHTO T51) in addition to (PG) to cope with rutting distress but not local specifications.

PG testing is performed using Dynamic Shear Rheometer (DSR) while elastic recovery is determined using subjective asphalt ductility test apparatus which is an empirical test that is conducted at 25°C (77°F) and does not predict the performance. This research aims to replace elastic recovery test with multiple stress creep recovery test (MSCR, AASHTO TP 70-08) for local mixes which can be performed using the Dynamic Shear Rheometer (DSR).

1.2 Discussion of the problem

1.2.1. Description of the problem

The Kingdom of Saudi Arabia has invested in a massive road network that is built according to the best international standards over the past thirty five years. Many more expressways and non expressways are built and maintained annually. Some of these roads have shown early signs of distresses due to the harsh environment and traffic load.

The environmental changes during the year, especially between summer and winter, and between day and night, are greatly affecting the durability of pavement asphalt. The high pavement temperature in summer (73°C) reduces the stiffness of paving mixture and consequently results in permanent rutting. On the other hand, low pavement temperature in winter (–10°C) reduces the flexibility of the paving mixture; thus, thermal cracks may develop.

Severe weather in some parts of the Kingdom has widely affected pavement performance and has resulted in pavement surface stripping. Increased loading on asphalt pavement roads due to the high growth rate in weight of trucks, traffic volume and tire pressure leads to an increased demand to modify asphalt binders by adding additives, such as polymers, fibers, and hydrocarbons. Use of polymers is the most convenient for of asphalt modification for local contractors. Several branded and non branded polymers are used locally.

Asphalt researchers use Superpave specification (AASHTO M320) to investigate the behavior of unmodified asphalt binders and classify them according to the performance grading system. But for the case of polymer modified asphalt binders, highway agencies tried to supplement the existing Superpave specifications with additional tests to evaluate correctly the behavior of the polymer modified asphalts. [John A. D'Angelo et al., 2009].

Elastic Recovery criterion is used for this purpose by many agencies worldwide. But in Saudi Arabia, Asphalt agencies still use the conventional Superpave standards and do not include the elastic recovery criteria in the evaluation. This additional test can only predict the presence of the polymer in the asphalt binder and does not evaluate the performance.

1.2.2. Approach to the Problem

In order to identify elastomeric polymer modified binders in terms of their fundamental properties and performance, the Multiple Stress Creep Recovery (MSCR) test (AASHTO TP 70-08) have been studied in this research to be introduced to the local standards. Such a test would replace the current empirical tests and offer the added advantage of compatibility with future specification tests.

This study includes investigation of the elastic properties of the modified Arabian asphalts from different sources with Honeywell Titans ^{TM}, SBS and Polybilt polymers. Percent recovery of the modified samples that have PG 70-16, PG 76-16 and PG 82-16 were determined using two methods; the conventional Elastic Recovery (ER) test using ductility bath (AASHTO T 51) and Multiple Stress Creep Recovery (MSCR) test (AASHTO TP 70-08). Results have been analyzed using statistical analysis to develop statistical model to enable the DSR to predict percent elastic recovery from MSCR test results.

1.3 Research Objectives

This research studied the recoverable strain criterion of polymer modified asphalts using two standard tests; MSCR and ER. The main objectives of this research project are:

- To evaluate the applicability of elastic recovery specifications of polymer modified local asphalts instead of the current Performance Grading system (PG).
- To replace the conventional Elastic Recovery (ER) test that utilizes the ductility apparatus with Multiple Stress Creep Recovery (MSCR) test for local asphalt binders which can be performed using Dynamic Shear Rheometer.
- To determine a statistical model for the relation between the ER and MSCR.
- To recommend minimum requirements of MSCR parameters (percent recovery) that can be used by MOT in Saudi Arabia.

1.4 Thesis Organization

This thesis consists of five chapters. Chapter 1 is an introduction chapter where the idea of road investment and improvement methods of asphalt mixtures were discussed. Chapter 2 contains detailed literature review and chapter 3 addressed the methodology used to conduct this research. Chapter 4 discussed the results of each test and analyzed them. Finally, chapter 5 highlights comparisons, conclusions and recommendations resulting from this research. In addition to this, Appendices A, B and C contain detailed results of PG, ER and MSCR test, respectively.

CHAPTER 2

LITERATURE REVIEW

2.1 Asphalt

Asphalts are multiphase systems with rheological behavior resembling that of the low-molecular-weight polymers [Stastna et al., 2000]. Because of the complexity of this material, the complete internal structure of asphalt is not known until now. Asphalts are highly dispersed and polymer-like materials that contain a broad distribution of various groups in their structure [Rassamdana et. al., 1996]. Researchers have derived thermodynamic models to describe the asphalt behavior [Wang and Buckley, 2001; Victorov and Smirnova, 1998] and still research in this area is going on. Large number of investigations have shown that asphalt properties (e.g., visco-elasticity and temperature susceptibility) can be improved by using an additives or a chemical reaction modification [Muncy et al., 1987; Collins and Bouldin, 1991; Bahia and Davis, 1994; Bonemazzi et al., 1996; Lu and Isacsson, 1997].

Among the different types of additives, polymers are the most promising modifiers. Asphalts in road paving applications are often modified by the use of small amounts (*i.e.* 4-8 as percent of binder weight) of polymers and there are more than 20 listed reasons in the literature for such modification [Becker et al., 2001]. Although there are a lot of polymers, only few are suitable for asphalt modification. Polymer modified asphalts obtained using mechanical mixing generally consist of two distinct phases due to dissimilarity of the two components [Brule, 1996]. The degree of improvement depends on polymer characteristics, asphalt characteristics, mixing conditions and compatibility of between asphalt and modification.

Improvement in rutting resistance, thermal cracking, fatigue damage, stripping, and temperature susceptibility have led polymer modified binders to be a substitute for asphalt in many paving and maintenance applications, including hot mix, cold mix, chip seals, hot and cold crack filling, patching, recycling, and slurry seal [Ali et al., 1994].

The Rheology (deformation and flow) of polymer-modified asphalts has received considerable attention over the years. Based on the findings of Strategic Highway Research Program (SHRP), it was concluded that fundamental viscoelastic behavior of asphalts, under different levels of stresses and temperatures, needs to be understood for performance-related specifications to address major pavement distresses.

2.2 Asphalt Modification

Asphalt is used with aggregates as binder in road construction. A little amount of asphalt causes significant change in asphalt aggregate mixture. Different factors determine the performance of asphalt binders. Unlike steel, which is considered a completely elastic material that can store energy indefinitely, asphalt binders cannot sustain a load without showing time-dependent deformation known as creep. When load is applied, some of the internal energy is dissipated in the material and results in a permanent set. This is called viscoelastic behavior.

2.3 Properties of Asphalt Binders

To minimize the deterioration of a flexible pavement due to influence from traffic and climate, the bituminous layer should: [Isacsson and Lu, 1995]:

- Be stiff enough at elevated temperatures to avoid permanent deformation (rutting).
- Show good fatigue resistance.
- Possess good stripping resistance (low water susceptibility).
- Show time independent properties (good ageing properties).
- Have good flexibility at low temperatures (resistance to low temperature cracking).
- Possess good wear resistance.

All the performance related properties of the mix are influenced by the binder properties. An ideal binder should have enhanced cohesion and very low temperature susceptibility throughout the range of temperatures to which was subjected in service, but low viscosity at the usual temperatures at which it is placed [Brule, 1996]. It was also mentioned that the susceptibility to loading time should be low, whereas its permanent deformation resistance, breaking strength, and fatigue characteristics should be high. In addition, it should have at least the same adhesion qualities as traditional binders and its ageing characteristics should be good both for laying and in service.

2.4 Asphalt Modifiers

Over the years, many different types of materials have been proposed as additives in bituminous mixes. Table 2.1 shows a compilation of groups of such additives. Different types of chemical reactions can also modify bitumen. The purpose of using a special additive in asphalt pavements is to achieve better road performance in one way or another.

Acid (poly-phosphoric acid) or alkaline (NaOH) modified asphalt was found to be only temporary and was reversible [Ho et al., 2002]. Acid modification of asphalt can be reversed by reaction with alkaline materials such as lime or anti stripping agents. Alkaline modification of asphalt can be reversed by reaction with acidic materials like CO_2. In this Study, only polymer-modified asphalt is discussed. For most of the groups listed in Table 2.1, a large number of products are available commercially.

There are three general types of asphalt modification; first group is the additive modifications like fillers, anti-stripping additives, extruders, anti-oxidants, etc. Second group contains polymer modification which is divided into two types depending on their behavior that include Plastomers, like Polyethylene and Polypropylene, and Elastomers like Styrene-butadiene-Styrene. Third group of asphalt modifications includes the chemical reaction modifications.

Table 2. 1. Types of asphalt modification [Isacsson et al., 1995].

	Type		Examples
I	Additive modification	1. Fillers.	Lime, carbon black, fly ash.
		2. Anti-stripping additives.	Organic amines and amides.
		3. Extenders.	Lignin, sulfur.
		4. Anti-oxidants.	Zinc anti-oxidants, lead anti-oxidants, phenolics, and amines.
		5.Organo-metal compounds.	Organo-manganese compounds, Organo-cobalt compounds.
		6. Others.	Shale oil, Gilsonite, silicone, inorganic fibers.
II	Polymer modification	1. Plastics (a) Thermoplastics. (b) Thermo-sets.	Polyethylene (PE), Polypropylene (PP), Polyvinyl chloride (PVC), Polystyrene (PS), Ethylene vinyl acetate (EVA). Epoxy resins.
		2. Elastomers. Natural rubbers. Synthetic rubbers.	Styrene-butadiene rubber (SBR), Styrene-butadiene-styrene (SBS), Ethylene-propylene diene terpolymer (EPDM), Isobutene-isoprene rubber (IIR).
		3. Reclaimed rubbers.	Crumb rubber
		4. Fibers.	Polyester fibers, Polypropylene fibers.
III	Chemical reaction modification		Addition reaction (bitumen + monomer), Vulcanization (bitumen + sulfur), Nitration reaction (bitumen + nitric acid).

2.5 Polymer Modified Asphalt (PMA)

A polymer is a large molecule that consists of one or more repeating units linked together by covalent bonds. A repeating unit is simply a group of atoms linked together covalently in a particular arrangement. Polyethylene (PE), Polyvinyl chloride (PVC), Polystyrene (PS), and Polyvinyl are some of the polymers widely used in polymer modification.

Polymer modification improves the asphalt binder performance. Isacsson and Zeng, [1998] studied the effect of styrene-butadiene-styrene polymer on low temperature cracking. It was concluded that the use of polymer-modified binder improves the resistance to thermally induced cracking at low-temperature.

Lu et al. [2001, 1998, and 1997] studied asphalt modification using different thermoplastics styrene butadiene styrene (SBS), styrene-ethylene/butadiene-styrene (SEBS), ethylene vinyl acetate (EVA) and ethylene butyl acrylate (EBA). It was found that the addition of these polymers increased the binder elasticity at high temperatures. The degree of modification, with respect to the binder Rheology, varied with temperature and frequency and is dependent on the bitumen source/grade and the polymer concentration and structure.

The effect of filler on low temperature hardening of bitumen was studied by Johansson and Isacsson [1998]. They used hydrated lime and calcium carbonate as fillers. Although no significant improvements were obtained, it was observed that physical hardening does not rely on molecular polarity but on free volume shrinkage.

Stastna et al. [2003] studied the viscosity of asphalt modified by SBS and EVA. They found that this blending produced a new material with different rheological properties. In this study, two shear thinning regions separated by a plateau region were obtained in high-temperature-viscosity curve. This indicates the formation of network and hence improvement in the properties of modified asphalt.

Yildirim [2007] reviewed the last three decades of research related to polymer modified binders including most used polymers like SBS, SBR, Elvaloy and rubber. These polymers have been used to design pavements for optimal performance. From the reviews he concluded that natural rubber improves rutting resistance and ductility, while SBR improves low-temperature ductility of the asphalt, improves elastic recovery and viscosity. SBS has been used in a wide range of products with asphalts to increases its elasticity in a significant way. Elvaloy also has a remarkable effect in increasing moisture resistance of the pavement and better performance at high temperatures.

Peng Y. et al. [2012] studied the performance improvements of asphalt binders modified with combination of SBS and waste polyethylene (WPE) in addition to Sulfur as a stabilizer. In this study, the modified asphalts with stabilizer were evaluated in terms of its physical and rheological properties in addition to viscosity and stability at high temperatures. The results show a significant improvement of these properties and concluded that the asphalt with SBS and PE has a remarkable creep recovery property to reduce the rutting of the pavement.

Ping et al., [2012] evaluate the influence of SBS polymer in improving the properties of asphalt binders and its effect on HMA mixtures. They selected two different mixes contain base asphalt (PG 67-22) with three SBS polymer contents of (3, 4.5 and 6%). The tests used in evaluation are tensile strength, creep compliance and resilient modulus at different temperatures; 25, 5 and -10 ºC. The results of this research show improvement in properties of SBS-polymer modified asphalt mixtures at low temperatures, namely stiffness, creep and failure strain properties.

Zhao et al. [2009] studied the polymer modified asphalt binders and mixes by using Superpave and conventional tests. They investigated different types of polymers include SBS, SBR, and complex polymers. From the comprehensive review of polymers in asphalt, it is shown that the properties of these modified asphalts and mixes vary with the type of polymer, dosage, asphalt source and type of aggregates and mix. As the amount of polymer increases the high and low temperature characteristics of the asphalt binder become better, also the creep stiffness decreases and aging characteristics would improve. The use of a polymer also enhances the dynamic stability of asphalt mix and the use of the rut depth can better measure the rut resistance. The presence of a polymer can also enhance the bending behavior of the asphalt mix at low temperatures.

Kök et al. [2011] evaluate the performance of asphalt when modified with SBS and Gilsonite at high temperature. The researchers tried to find a natural source of polymers to replace the industrial ones and find the optimum content of that polymer depending on the rheological testing. They studied the two polymers separately and then studied them together. The results show that around 3–4% times more Gilsonite is needed to replace 1% of SBS when the two modifiers are mixed in the same binder depending on the selected Gilsonite/SBS ratio. Besides, the viscosity of modified binders with a percent of SBS replaced with Gilsonite is always lower than that of SBS-only modified binder. It is suggested that Gilsonite can be used as an alternative modifier to reduce the cost of asphalt mixture production and compaction in the field.

Wong et al. [2004] studied the rutting resistance of unmodified and polymer modified asphalt binders by introducing a stiffness indicator of Generalized Dynamic Shear Modulus (GDSM). The shear stress and shear strain are obtained for each binder by using Dynamic Shear Rheometer (DRS). Two types of mixtures that have different aggregate gradation were evaluated for rutting resistance. Results from this research indicate that there is a good correlation between GDSM and the average rutting depth and it is confirmed that GDSM is useful as a stiffness indicator for the evaluation of rutting resistance of binders.

Ruan et al. [2003] studied the effect of long-term aging on rheological properties of polymer modified asphalt binders with tire rubber, SBS and SBR polymers to evaluate the aging properties of asphalt in a controlled environmental room at 60 ^{o}C or 100 ^{o}C (PAV) test. Test results have shown that, for the polymer modified asphalts, the complex modulus increases at high temperatures and decreases at low temperatures and durability improved. At oxidation conditions of these modified asphalts, the temperature susceptibility decreases and the network of the polymer in the binders which diminish polymer effectiveness in improving asphalt ductility.

Green Car Congress [2013] has published a study utilizing Honeywell Titan™ additives as compared to traditional ones. his study has indicated that Honeywell Titan™ additives has many advantages; it help in decreasing the harmful emission by about 82% and 13% reduction in energy consumed in mixing and paving processes due to reducing the fluidity of the mix by 70% comparing to other commonly used additives and polymers. It also can help to minimize rutting. Another advantage of this additive is that it reduces the amount of required additive by approximately 30% depending on the source and type of asphalt.

Shenoy [2004] realized from his study that the parameter related to Superpave specification $|G^*|/\sin\delta$ is not adequate in performance grading of polymer modified binders at high temperatures. Efforts were spent to modify this parameter and make it more sensitive and find other parameters that better relate to rutting resistance. In his work a new parameter is introduced to refine the Superpave specifications parameter depending on fundamental basis which is $|G^*|/ (1-(1/\tan\delta \sin\delta))$. The author concluded that the modification in parameters led to better simulation of rutting resistance of modified asphalts modified with polymers, and proposed to use this parameter as high temperature grading specifications for this type of asphalts and evaluate its efficiency in the field.

Eileen et al. [2011] presented a correlation of elastic recovery and molecular weight with multiple stress creep and recovery (MSCR) parameters of different polymer modified binders. MSCR used to measure % strain and (J_{nr}) which is non-recoverable creep compliance parameter; these parameters are used to predict the behavior of polymer modified asphalts at high temperatures in resisting rutting, fatigue and thermal cracks. The results of analysis in this study show a positive correlation between recovery from MSCR at 64ºC and elastic recovery at 25ºC while a negative correlation was found between (J_{nr}) and elastic recovery.

Shirodkar et al. [2012] studied the multiple stress creep and recovery (MSCR) curve to characterize polymer modified binders. Two parameters are measured from the curve, non-recoverable compliance (J_{nr}) and the % recovery. The linear, non-linear and non-recoverable compliance was similar between cycles. The non-recoverable compliance was sensitive to base binder, PPA, Elvaloy and SBS polymers. The results show that the permanent strain calculated from the (MSCR) procedure is lower than non-recoverable strain measured at the end of 10 seconds. Also the sensitivity of the different parameters to polymer modification should be evaluated to provide a better understanding on how a given polymer influences the mechanical behavior of a given binder.

Wasage et al. [2011] conducted a study that considered the non-recoverable compliance J_{nr} as a new parameter to evaluate the rutting behavior of polymer modified asphalt binders using the Multiple Stress Creep and Recovery (MSCR) test. This test is suggested to replace the conventional Superpave standards for rutting criteria at high-temperatures. ($G^*/\sin\delta$). The study includes an investigation of the newly suggested parameter to capture the rutting behavior and rheological analysis of the MSCR by conducting the laboratory wheel tracking test of the asphalt mix and create a correlation between J_{nr} and rutting for theses mixes. They concluded from their study that the best correlation between J_{nr} and rut depth was obtained at high-levels of stress from the MSCR.

Clopotel and Bahia [2012] studied the elastic recovery of polymer modified asphalt binders by using two methods; Dynamic Shear Rheometer (ER-DSR) and Ductility Bath (ER-DB). They concluded that there is a good correlation between the two methods with some benefits of DSR which needs less material and it is more time efficient. They compared their DSR results with pavement performance to establish a link between them, they recommends to replace the conventional (ER-DB) with (ER-DSR).

D' Angelo [2009] studied the validation of MSCR non-recoverable compliance (Jnr) to rutting criteria of the polymer modified asphalt binders. His study included the use of extensive mix testing using laboratory rut testers, accelerated load facilities and actual sections of the roadway. He concluded that the MSCR test can provide better correlation to mixture rutting than the conventional Superpave criteria of the binder based on the results he found during the study.

2.6 Arabian Polymer Modified Asphalt

In 1994, Al-Abdul Wahhab et al., adapted SHRP binder performance specifications for the environment of the Gulf Countries (GCs). GCs were divided into different zones and the required asphalt performance grade (PG) for each zone was specified as shown in Figure 2.1.

It was found that the asphalt cement as used locally in the Gulf area is only suitable for about 40% of the GCs area. In fact, there are only few types of crude that can produce very good asphalts, and only a limited number of actions that can be taken to control the refining process to make improved asphalts; beside that, the neat asphalt binders lack the proper viscoelastic balance that usually occurs when an effective elastic network is created by molecular association.

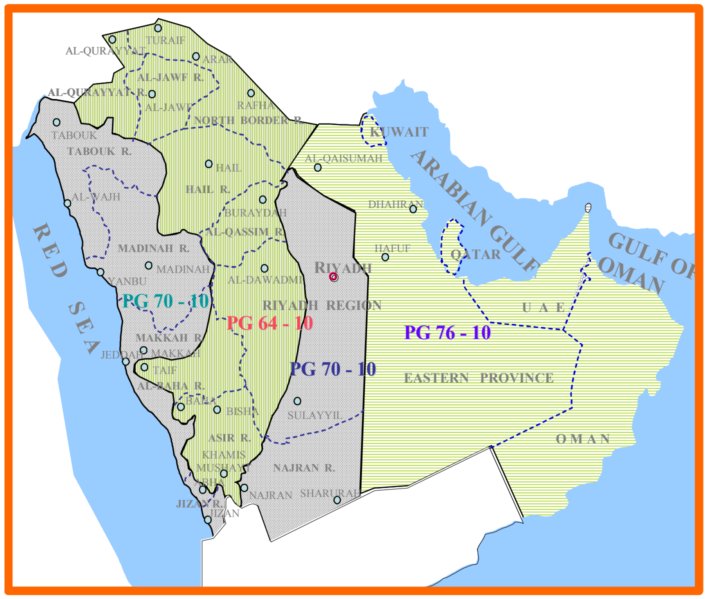


Figure 2. 1. Details of the temperature zones in the Gulf Area
[Al-Abdul Wahhab et al., 1994].

Several research projects [Al-Abdul Wahhab et al., 1996, 1997, 1999, 2002]; Ali et al., 1999; Al-Dubabe et al., 1998; Asi et al., 1997] followed the temperature zoning study, and conducted research to modify asphalt in order to achieve the PG requirements. Several attempts have been made to modify the Arabian asphalt and determine the associated change in rheological properties. Many polymers have been used as asphalt modifiers, and they can be classified into eight groups:

- High Density Polyethylene (HDPE) from SABIC.
- Linear Low Density Polyethylene (LLDPE) from SABIC.
- Medium Density Polyethylene (MDPE) from SABIC.
- Polypropylene (PP).
- Styrenic Heavy Waste (SHW).
- Styrene-Butadiene-Styrene (SBS).

- Crumb Rubber (CR).
- Polybilt (PB).

These eight groups include fifteen different polymers used to modify asphalts and each has shown its own associated physical properties. For example, LLDPE stiffens the asphalt, much like a hard plastic, so it is considered a plastomer. SBS can increase the elasticity of the asphalt, much like a rubber band, so they are considered elastomers. At the initial stage, some of these polymers were rejected because they possess a very high melting temperature; eight types of polymer from a total of fifteen were found to be suitable for blending with asphalt. The polymers that have a flow temperature of more than 180°C were rejected.

2.7 Summary

Improvement in rutting resistance has led polymer modified binders to be a substitute for asphalt in many paving and maintenance applications and viscoelastic behavior of asphalts, under different levels of stresses and temperatures, needs to be understood for performance-related specifications to address major pavement distresses. It was found that the susceptibility to loading time should be low, whereas its permanent deformation resistance should be high. Studies show that Superpave Performance Grading is not sufficient to be used for evaluation of polymer modified asphalts and additional tests like Elastic Recovery should be used. Some researchers studied the relation between Elastic Recovery and Multiple Stress Creep Recovery tests but no one had studied the correlation between the two tests and determined a model and specific limit for the new test to be used instead of the empirical Elastic recovery and his is the main target of this research.

CHAPTER 3

METHODOLOGY

3.1 Material Selection

3.1.1. Asphalt binders

Asphalt cement samples were collected in cooperation with Saudi ARAMCO from four asphalt producing refineries at Ras Tanura (Rt), Riyadh (Ry), Jeddah (Jd) and Yanbu (Yb). These four refineries are selected in this study because they cover different temperature zones of the Kingdom and have the largest daily production amounts of asphalt binders.

3.1.2. Polymers

Four types of commercial polymers which are most used in local projects were selected to conduct the modification of asphalt binders in this study. Table 3.1 lists typical properties of these polymers and Figure 3.1 shows the proposed polymers to be used in the study. These polymer are divided into two subgroups in terms of their behavior; elastomers like SBS and plastomers like Titans and Polybilt 101.

Figure 3. 1. Commercial polymers used in the study.

Table 3. 1. Typical properties of the polymers in the study.

Property	SBS	Polybilt	Titan 7686	Titan 7205
Density	0.90 g/cc	0.943 g/cc	0.99 g/cc	0.93 g/cc
Viscosity at 150°C Brookfield	400 - 4320 cPs.	600 cPs.	450 cPs.	450 cPs.
Product form	Prill	Prill	Granule	Prill
Size	4-6 mm diameter	6-8 mm	100%	2-3 mm
Bulk Density	400 kg/m^3	350 kg/m^3	625 kg/m^3	508 kg/m^3

3.2 Experimental Design

SBS, Polybilt and Titans polymers are tested in combination with four sources of Arabian Asphalts. Different levels of each polymer as percent of binder weight are used starting from zero percent (neat asphalt) up to 6% of asphalt binder weight. Table 3.2 shows the combinations of the experimental design.

The first step of the testing procedure is to find the performance grade of each asphalt-polymer combination; since there are four types of polymers and two hybrid combination of polymers and four sources of asphalt, the total number of samples is 124 as mentioned in Table 3.2. After that, the modified asphalt binders with known Performance Grade are tested for percent recovery evaluation using two methods; Elastic Recovery and Multiple Stress Creep Recovery tests.

Table 3. 2 Experimental design.

Test	Asphalt Binder Sources	Polymer Type	Polymer Level	Total number of combinations
Performance Grading tests	Riyadh (Ry), Ras Tanura (Rt), Jeddah (Jd) and Yanbu (Yb).	Titan 7686 Titan 7205 SBS Polybilt None(Neat Asphalt)	2% - 6%	100
	Riyadh (Ry), Ras Tanura (Rt), Jeddah (Jd) and Yanbu (Yb).	Titan 7686 : SBS (1:1) Titan 7205: SBS (1:1)	3% -5%	24
MSCR and ER tests	Riyadh (Ry), Ras Tanura (Rt), Jeddah (Jd) and Yanbu (Yb).	Titan 7686 Titan 7205 SBS Polybilt Titan 7686 : SBS (1:1) Titan 7205: SBS (1:1) None (Neat asphalt)	% Polymer that achieves PG 70-16, PG 76-16 and PG 82-16	84

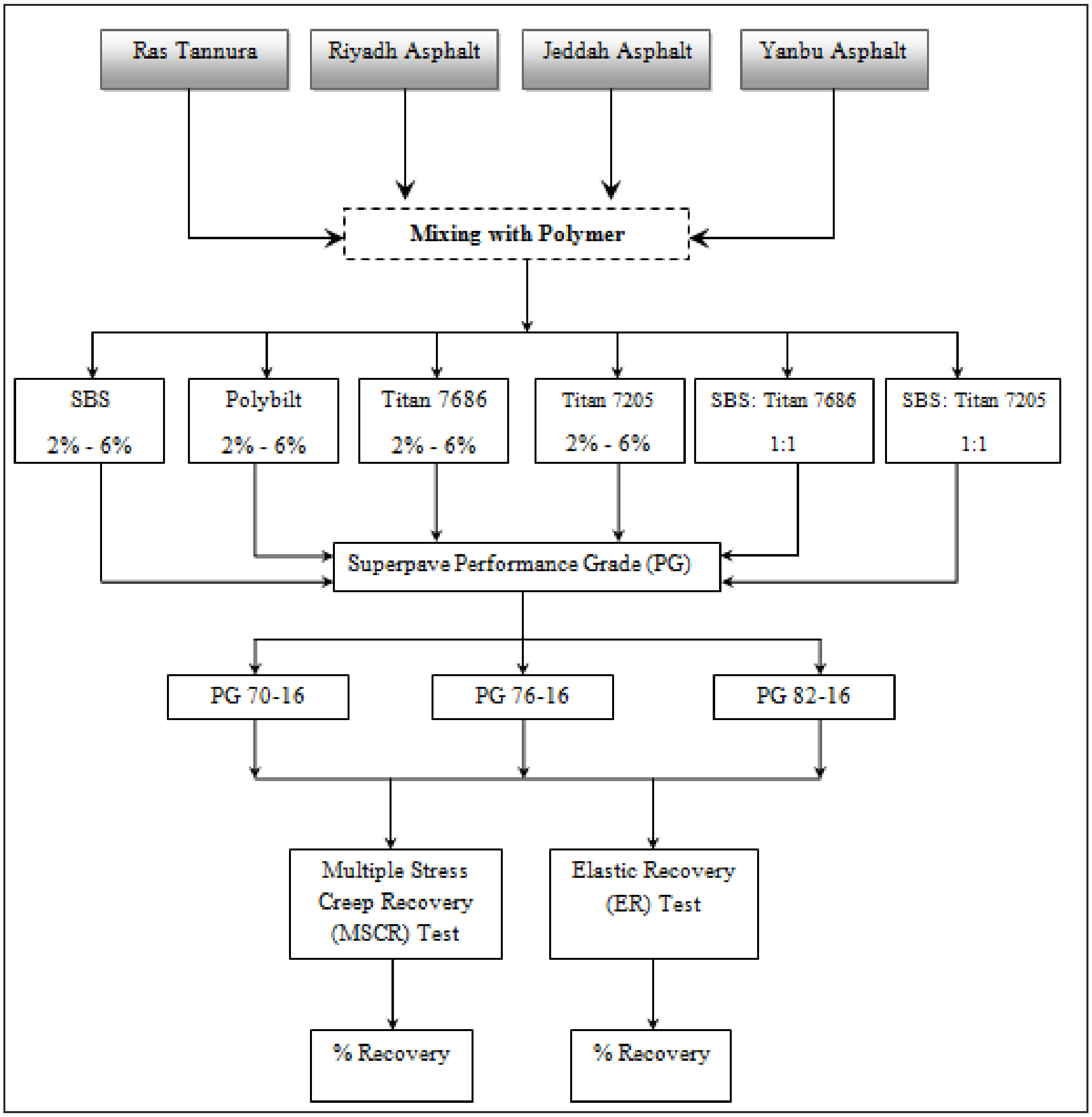


Figure 3. 2. Flow chart of the experimental work.

Figure 3.2 summarizes the experimental work which was conducted in this research. First step is to select asphalt source and polymer type and amount, then create the PG system of all tested samples. Finally evaluate the recovery characteristics of the polymer modified asphalts which have grades of PG 70-16, PG 76-16 and PG 82-16. Moreover, correlation between MSCR and ER percent recovery values is obtained

3.3. Sample preparation and testing

Mixing, sample preparation and testing is followed by AASHTO and ASTM Standards.

3.3.1. Blending Sequences for polymer-asphalts combinations

Before preparing the samples to be tested, neat asphalt should be mixed properly with polymer; each polymer has specific mixing procedure described as follows:

Asphalt is heated to specific temperature and the polymer is stirred in using shear mixing as simple propeller type bale, spun at 800 PRM shown in Figure 3.3.

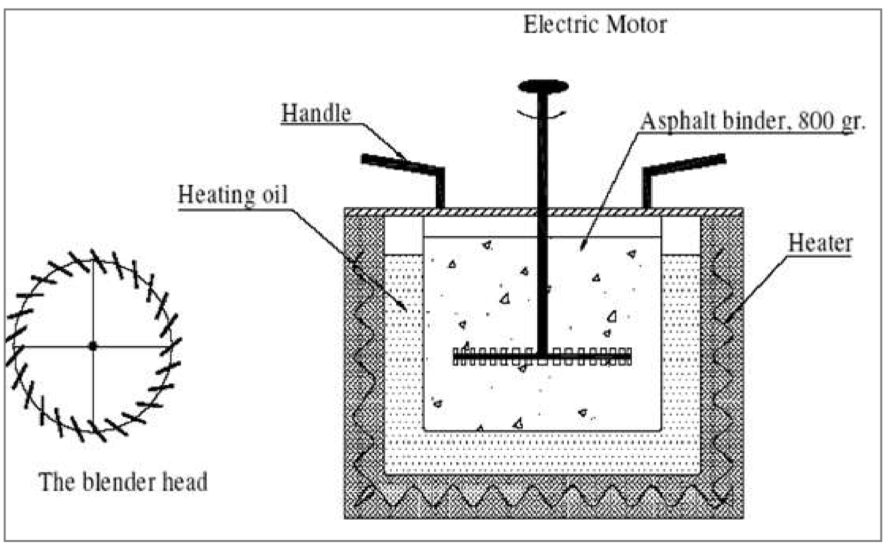


Figure 3. 3. Shear mixer.

Once the asphalt reaches temperature and is uniform, Honeywell Polymers were added gradually. Asphalt samples were treated with 2, 3, 4, 5, and 6% Titan polymers. The polymers are simply sprinkled on the asphalt surface and mixed for one hour.

For Polybilt polymer the mixing is carried out at 165 °C for a minimum of one hour, as the Polybilt needs a higher temperature to disperse than the Honeywell™ Titan.

When SBS polymers and their hybrid combinations are used, the mixing is carried out at 180-183 °C with high shear mixing (around 5000 rpm) for a minimum of two hours. Samples are Stored at around 145 °C overnight in an oven to mature the SBS network. Samples were heated in an oven at 180 °C, and then mixed for 15-20 min in the shear mixer at 180 °C (at 800 rpm) before testing specimens can be prepared.

3.3.2. Flash Point and Viscosity

The Performance Grading (PG) system (AASHTO M320, ASTM D6373) was used to grade plain and modified asphalts. Dynamic viscosity (AASHTO TP48, ASTM 4402) was carried on the modified asphalt to determine asphalt workability, mixing and compaction temperatures based on viscosity. Flash point (AASHTO T48, ASTM 449), safety test, was also determined.

3.3.3. Rolling Thin Film Oven (RTFO)

The RTFO test (AASHTO T-240, ASTM D 2872) was used to simulate the aging that takes place during the production and up to the first year life of the pavement. The base asphalt as well as modified asphalt was poured into cylindrical bottles. Figure 3.4 represents RTFO machine and RTFO bottles before and after RTFO test.

35 grams of asphalt sample was poured in each cylindrical bottle. Then the bottles were placed horizontally in a convection oven, which was rotated at 163 ^{o}C for 85 min. This process created a thin film of asphalt on the inside of the bottles. After the test the sample was collected for further tests. Dynamic Shear Rheometer (DSR) testing before and after RTFO was done to investigate the short term aging effect of asphalt mixes.

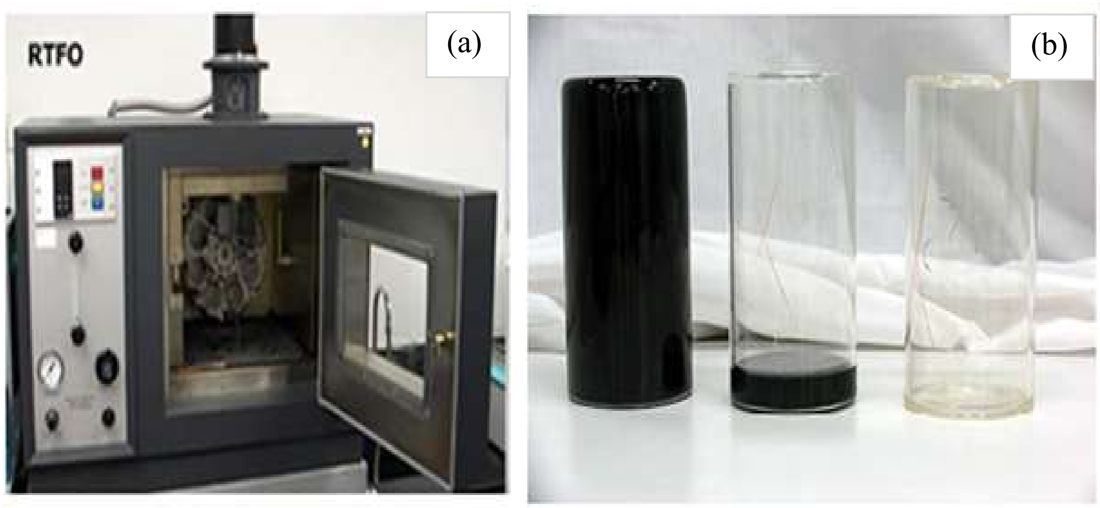


Figure 3. 4. Rolling Thin Film Oven Test

(a) Rolling Thin Film Oven (RTFO) machine, (b) RTFO bottles, bottle at left is after the RTFO test, the bottle in the middle is before the test.

3.3.4. Pressure Ageing Vessel (PAV)

The pressure ageing vessel (PAV) (AASHTO R28, ASTM 6521) has been developed to simulate in-service ageing of asphalt binder after 5 to 10 years. The binder is exposed to high pressure and temperature for 20 hours to simulate the effect of long term oxidative ageing. The apparatus consists of a stainless steel pressure vessel with encased band heaters and integral pressure and temperature controls. Platinum RTD measures internal test temperature to ±0.1 °C. Selectable test temperatures (standard 90/100/110 °C) are controlled to ±0.2 °C. Pressure is monitored by a transducer and controlled to 2.1 ± 0.1 MPa. The RTFO aged binder was placed in shallow pans approximately 3 mm thick. Figure 3.5 shows the PAV machine and sample accessories. During the PAV process, air was driven into the binder. The sample was placed in the PAV for 20 hours at 2.1 MPa and 100 ^{o}C. The sample was then collected for further tests to complete this PG test.

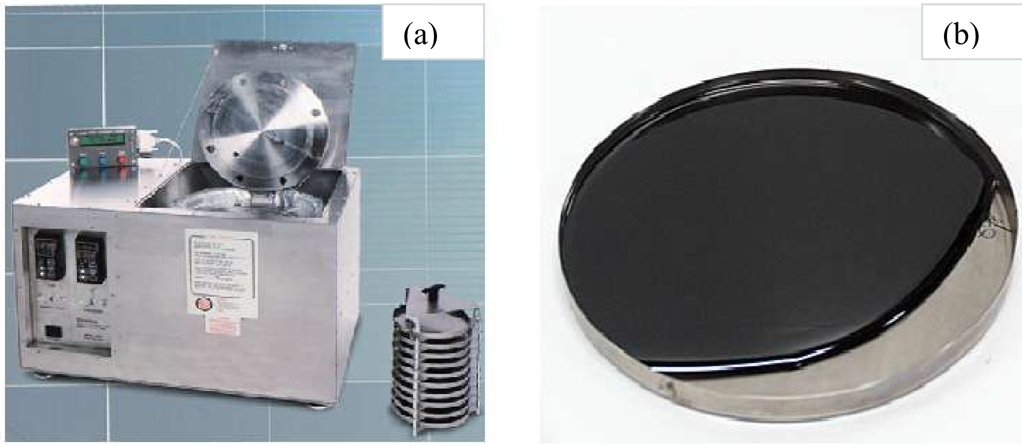


Figure 3. 5. Pressure Ageing Vessel Test

(a) PAV machine, (b) RTFO residue poured in pan for PAV test.

3.3.5. Dynamic Shear Rheometer (DSR)

The dynamic temperature step measurements for the samples were performed in CSA II rheometer. Figure 3.6 shows the ARES and CSA II Rheometers used in this research. All tests were carried out in a range of 64^{o} C-82^{o}C using a parallel plate set of diameter is 8 mm or 25 mm depending on the sample age. Strain in the linear viscoelastic range and frequency of 10 rad/s was used for all the tests (AASHTO T315, ASTM 7175). Sample is given the required time to reach the desired test temperature (with in $\pm 0.1^{o}$C) then the DSR will automatically start holding period of 10 min. to allow the temperature to reach steady state plus 2 minutes was allowed before beginning measurements. Special software was used to calculate the dynamic shear viscosity, storage modulus and PG grading for all samples. Fresh asphalt and RTFO residue was run in DSR with plate diameter 25 mm. Asphalt samples were tested after PAV and became harder than that of fresh asphalt. Therefore, asphalt submersion cell with 8 mm diameter plate was used for PAV residue sample.

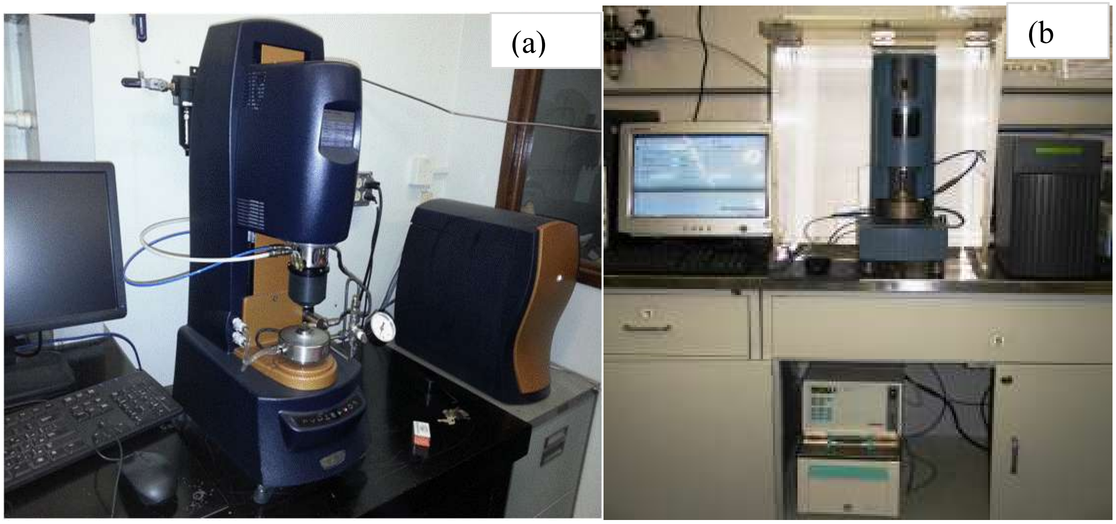


Figure 3. 6. Dynamic Shear Rheometer

(a) HR-3 Discovery Hybrid Rheometer (b) CSA II Rheometer.

3.3.6. Bending Beam Rheometer (BBR)

The Bending Beam Rheometer (BBR) test (AASHTO T313, ASTM D6648) provides a measure of low temperature stiffness and relaxation properties of asphalt binders. These parameters give an indication of an asphalt binder's ability to resist low temperature cracking. The BBR is used in combination with the DTT to determine an asphalt binder's low temperature PG grade. As with other Superpave binder tests, the actual temperatures anticipated in the area where the asphalt binder will be placed, determine the test temperatures used. Because low temperature cracking is a phenomenon found mostly in older pavements, the test is run on the long-term aged residue from the PAV. Figure 3.7 shows the photograph of BBR and mold to prepare beam for test.

Figure 3. 7. Bending Beam Rheometer (BBR) Test

(a) BBR Machine, (b) Mold accessories for making asphalt binder beam.

3.3.7. Performance Grading (PG) System

Performance Grading (PG) of asphalt binder (AASHTO M320, ASTM D6373) was determined based on several tests of fresh and aged asphalt binder. The machineries used to short and long term ageing are RTFO and PAV. Fresh asphalt binder as well as residue from RTFO and PAV was tested as the sequence presented in Figure 3.8.The complete PG was determined using data acquired from Superpave tests.

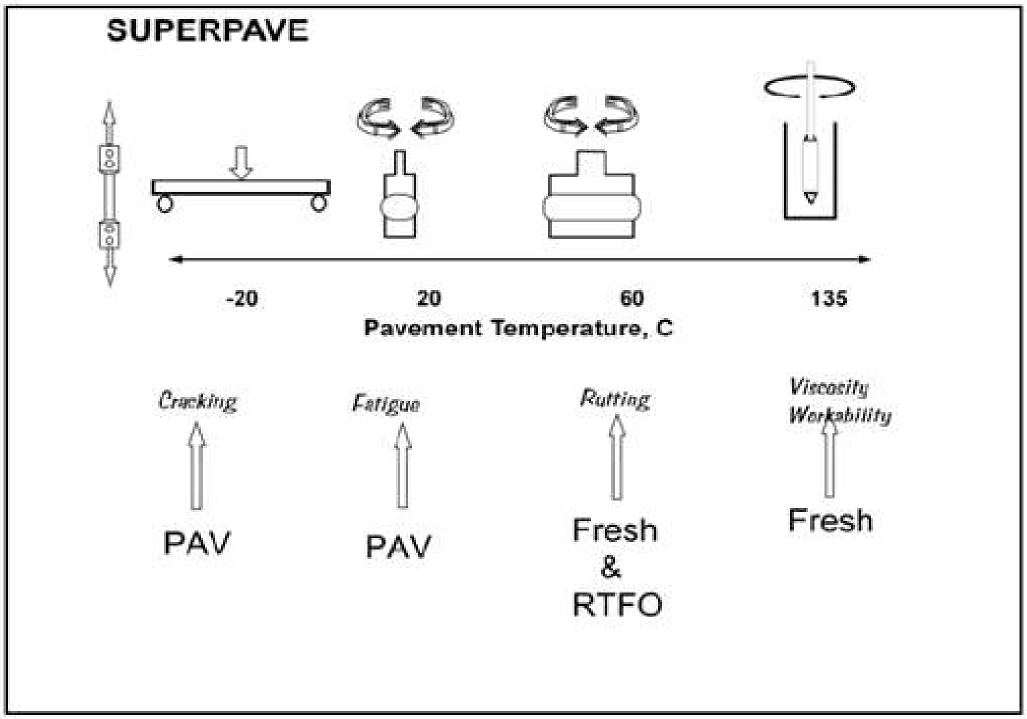


Figure 3. 8. Summary of Superpave asphalt binder specification tests.

The existing SHRP specification of performance grade system does not have criteria for durability and fatigue and also does not identify the performance characteristics of modified binders. Thus, many agencies look to other tests to identify elastomeric polymer modifiers, such as Elastic Recovery, Toughness and Tenacity. [John A. D' Angelo, 200].

3.3.8. Elastic Recovery utilizing the Ductility Bath

The percentage of recoverable strain is used to evaluate the Elastic Recovery (ER) of polymer modified binders. This test is performed by utilizing the conventional ductility test (AASHTO T 51) at 25±0.5°C (77°F) and with speed of 50 mm/min ± 5.0%.

The sample is poured in the standard mold as shown in Figure 3.9 and then subjected to elongation at specified conditions to have a deformation value, and the distance to recover this deformation after 1 hour is recorded and the percent recoverable strain is calculated. Figure 3.9 describes the steps for the test.

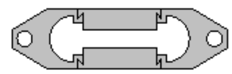
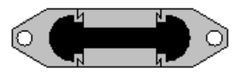
Standard mold	
The Mold is filled with RTFO residue of modified binder, AASHTO T 51	
The test specimen is elongated at the specified rate to a deformation of 100mm.	
Immediately, the sample is cut into two halves at the midpoint	
After one hour, the two parts of the mold are moved to touch each others and measure the differance	

Figure 3. 9. Elastic Recovery Test procedure.

The value of percentage of recoverable strain is calculated by equation 3.1.

$$\text{Percent Recovery (\%R)} = \frac{(100-X)}{100} \text{ x } 100\% \qquad (3.1)$$

Where (x) is specimen length in mm. The values of percent recovery were recorded for each combination of polymer (type and amount) and asphalt source. To recommend a standard limit of ER test, [Eileen et al., 2011 and John A. D' Angelo 2009] studied the elastic recovery of different modified asphalt-polymer combination and used a limit of 60% as percent recovery using this test, and found that all the acceptable samples should have more that this limit.

In this research, all the elastic recovery results were compared to the recommended limit of percent recovery (%R) mentioned in the previous studies. Since this limit had been used by many asphalt agencies and research centers around the world.

3.3.9. Multiple Stress Creep Recovery (MSCR) test

This test method covers the determination of percent recovery and non-recoverable creep compliance (Jnr) of asphalt binders by means of the Multiple Stress Creep Recovery (MSCR) test. The MSCR test is conducted using the Dynamic Shear Rheometer (DSR) at a specified temperature. It is intended for use with residue from (T 240 Rolling Thin-Film Oven Test (RTFOT)).

The percent recovery value is intended to provide a mean of determining the elastic response and stress dependence of polymer modified and unmodified asphalt binders.

This test method is used to determine the presence of elastic response in an asphalt binder under shear creep and recovery at two stress levels at a specified temperature. For performance-graded (PG) asphalt binders, the specified temperature will typically be the PG high temperature from (AASHTO MP 19).

Asphalt binder is first conditioned using (AASHTO T 240, RTFO). A sample of the RTFO-conditioned asphalt is tested using (AASHTO T 315, DSR). The 25-mm parallel plate geometry is used with a 1-mm gap setting. The sample is tested in creep at two stress levels followed by recovery at each stress level. The stress levels used are 0.1 kPa and 3.2 kPa. The creep portion of the test lasts for 1 second, which is followed by a 9-second recovery. Ten creep and recovery cycles are tested at each stress level.

Non-recoverable creep compliance (Jnr) has been shown to be an indicator of the resistance of an asphalt binder to permanent deformation under repeated load.

Figure 3.10 shows one of the ten cycles of creep and retardation response that the binder behaves by evaluating the strain.

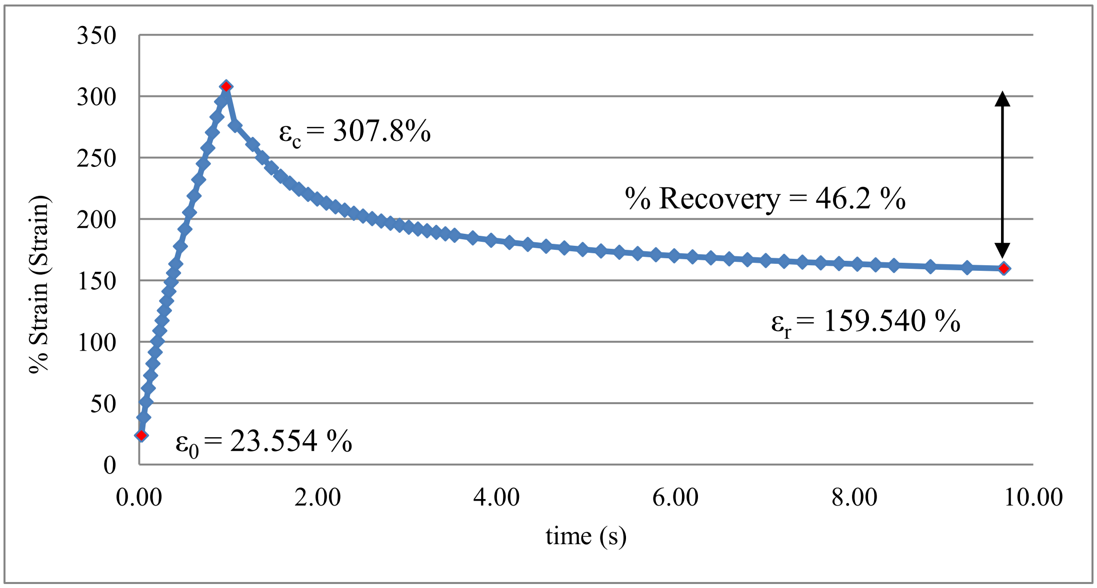


Figure 3. 10. Test Cycle No. 1 Data Plot showing Creep and Recovery at Creep Stress of 100 Pa.

In order to calculate % recovery at each stress value, start and end points of creep and recovery curves should be determined. Creep curve can be defined with its starting point noted by ε_o and its end with ε_c after 1 second of loading. And for the recovery part, it starts at the creep end point ε_c to reach the minimum value of strain at ε_r after 9 seconds of recovery.

The equations used to calculate the % recovery and non-recoverable compliance (Jnr) by following the (AASHTO TP 70) method of test are:

The adjusted strain value at the end of the creep portion of each cycle (ε_1):

$$\varepsilon_1 = \varepsilon_c - \varepsilon_o \tag{3.2}$$

The adjusted strain value at the end of the recovery portion of each cycle (ε_{10}):

$$\varepsilon_{10} = \varepsilon_r - \varepsilon_o \tag{3.3}$$

Percent recovery for each cycle at 0.1 kPa stress level

$$\varepsilon_r (0.1, N) = \frac{(\varepsilon_1 - \varepsilon_{10}) \text{x } 100}{\varepsilon_1} \tag{3.4}$$

Average percent recovery of 10 cycles at 0.1 kPa stress

$$\%R_{0.1} = \frac{\sum[\varepsilon_r(0.1,N)]}{10}, \text{ for N from 1 to 10} \tag{3.5}$$

Percent recovery for each cycle at 3.2 kPa stress level

$$\varepsilon_r (3.2, N) = \frac{(\varepsilon_1 - \varepsilon_{10}) \text{x } 100}{\varepsilon_1} \tag{3.6}$$

Average percent recovery of 10 cycles at 3.2 kPa stress

$$\%R_{3.2} = \frac{\sum[\varepsilon_r(3.2,N)]}{10}, \text{ for N from 1 to 10} \tag{3.7}$$

Percent difference in recovery between the two stress levels

$$R_{diff} = \frac{(R_{0.1} - R_{3.2}) \text{x } 100}{R_{0.1}} \tag{3.8}$$

According to the FHWA, the value of R_{diff} should be more than 75%

To calculate the non-recoverable compliance (J_{nr}) between 0.1 kPa and 3.2 kPa. For each ten cycles at a creep stress of 0.1 kPa, J_{nr} (0.1, N), kPa^{-1}

$$J_{nr} (0.1, N) = \frac{\varepsilon_{10}}{0.1} \tag{3.9}$$

For each ten cycles at a creep stress of 0.1 kPa, J_{nr} (3.2, N), kPa^{-1}

$$J_{nr}(3.2, N) = \frac{\varepsilon_{10}}{3.2} \tag{3.10}$$

Average Jnr of 10 cycles at 0.1 kPa stress

$$Jnr_{0.1} = \frac{\sum[J_{nr}(0.1,N)]}{10}, \text{ for N from 1 to 10} \tag{3.11}$$

Average Jnr of 10 cycles at 3.2 kPa stress

$$Jnr_{3.2} = \frac{\sum[J_{nr}(3.2,N)]}{10}, \text{ for N from 1 to 10} \tag{3.12}$$

Calculate the percent difference in non-recoverable creep compliance between 0.1 kPa and 3.2 kPa, Jnr_{diff}

$$Jnr_{diff} = \frac{(Jnr_{3.2} - Jnr_{0.1}) \text{x } 100}{Jnr_{0.1}} \tag{3.13}$$

MSCR parameters, namely; Percent Recovery and Jnr, should be studied together. General relation between both test results showed that the relation is inversely proportional. However, there is no exact value accepted by AASHTO for evaluation of polymer modified asphalts using MSCR test, but many asphalt agencies and researchers studied the MSCR recommended values of percent recovery (%R) and non-recoverable compliance (Jnr).

AASHTO TP 70 states that if the percent recovery plots above the line (defined by the equation $y = 29.37(x)^{-0.263}$, where x = average Jnr at 3.2 kPa and y = percent recovery), the binder is modified with an acceptable elastomeric polymer. A system of "pass/fail" to be considered like the one specified in AASHTO TP 70, or for setting a minimum acceptable percent recovery. Figure 3.11 shows the recommended curve with pass/fail system.

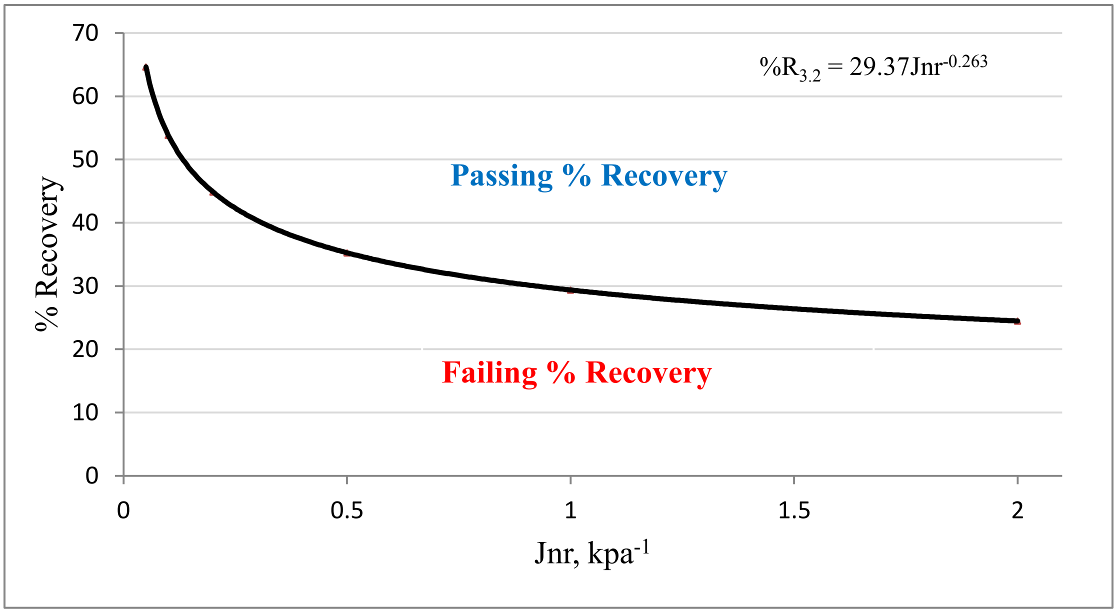


Figure 3. 11. Standard curve for delayed-elastic response
(FHWA, 2009).

This standard curve indicates that even if PG 82-16 asphalts are acceptable by the Superpave performance grading standards, but may fail in terms of elastic recovery at high stress levels.

John A. D' Angelo [2009] recommended value of percent recovery of 20% to be the minimum accepted for polymer modified asphalt at 3.2 kPa stress.

CHAPTER 4

RESULTS AND ANALYSIS

4.1. Superpave ^{TM} Performance Grading (PG) system

Polymer modified asphalt binders should be designed to resist Rutting at high and intermediate temperatures and Fatigue cracking at low temperatures. The modified samples were tested under three ageing conditions; fresh, short-term as a residue from Rolling Thin Film Oven (RTFO) and long term as a residue from Pressure Ageing Vessel (PAV).

Samples were tested at different temperatures starting from 64°C up to 82°C with 6 degrees increments to determine the PG high-service grade temperature to simulate rutting behavior of the asphalt binder. For the PG low-service temperature, samples were tested at -16°C which simulate the fatigue behavior of the polymer modified binder.

Results were analyzed using regression analysis to obtain actual grade temperature that the sample can withstand the value of G*/sinδ equals to 1 kPa for original conditions, and 2.2 kPa for short term-ageing conditions, the lowest grade of the two conditions is selected to be the upper grade of that modified sample.

For the intermediate temperature testing, the long term aged samples should have G*sinδ less than 5 MPa for standard grade traffic and 6 Mpa for High, Very high and Extremely high traffic conditions. Moreover, fatigue resistance evaluation procedure states that all modified samples tested at -16°C should have stiffness (S) less than 300 Mpa and slope

(m) more than 0.3. Table 4.1. shows the Superpave PG summary sheet used in the analysis.

Table 4. 1. Asphalt PG Summary Sheet.

King Fahd University of Petroleum & Minerals, Dhahran File#264

Civil Engineering Department

Asphalt Grading Summary Sheet - SHRP Binder Performance

Asphalt ID:	Rt	Ry	Jd	Yb	
Additive:	None	SBS	Titan 7686	Titan 7205	Polybilt
Date :					

Grade	Original	RTFOT	RTFOT + PAV residue					
	Flash Pt: 326° C (Min: 230° C) Viscosity at 135°C: 718.5 cP (Max: 3000 cP)	Loss: % (Max: 1.0%)	Time/Temp after PAV: 20 HRS @ 110°C					
	Dynamic Shear 10 rad/s (1.6Hz)	Dynamic Shear 10 rad/s (1.6Hz)	Dynamic Shear 10 rad/s (1.6Hz)		Flexural Creep (at 60 sec)			DT * (1mm/min)
	G*/sind (kPa) > 1 kPa	G*/sind (kPa) > 2.2 kPa	Temp °C	G*sind (MPa) < 5 MPa, "S" Grade < 6 MPa, "H", "V", "E" Grades	Temp °C	Stiffness, S < 300 MPa	Slope, m > 0.30	F. Strain > 1.0%
PG 70	2.609 kPa	3.896 kPa	34		0			
			31		-6			
			28		-12			
			25		-18			
			22		-24			
PG 76	1.5807 kPa	2.196 kPa	37	0.54899	0			
			34	0.82136	-6	71.6649	0.38128	
			31		-12			
			28		-18			
PG 82	1.2065 kPa	kPa	40		0			
			37		-6			
			34		-12			
			31		-18			

* Required only if Creep Stiffness (S) is between 300 and 600 Mpa, and m > 0.30

Sample Grade: PG 76-16

4.1.1. Relation between temperature and G/sinδ*

Tested samples, besides neat asphalt, have 2-6% of polymers by the binder weight for each type of polymer and tested at different temperatures starting from 64 °C up to 82 °C and different ageing conditions.

Change in temperature and ageing conditions affects significantly the visco-elastic behavior of the modified asphalt. If temperature increases, G*/sinδ will decrease due to reduction of viscosity and elasticity. Short term ageing conditions show higher values of G*/sinδ than fresh conditions for each polymer due to the increase in ageing and viscosity.

Polymers of different types have remarkable influence in improving the elastic and viscous performance of the asphalt binder. Figures 4.1-a and 4.1-b show the results of Ras Tannura asphalts modified with Titan 7686 polymer at original and short-term ageing conditions, respectively. Other samples are listed in Appendix A.

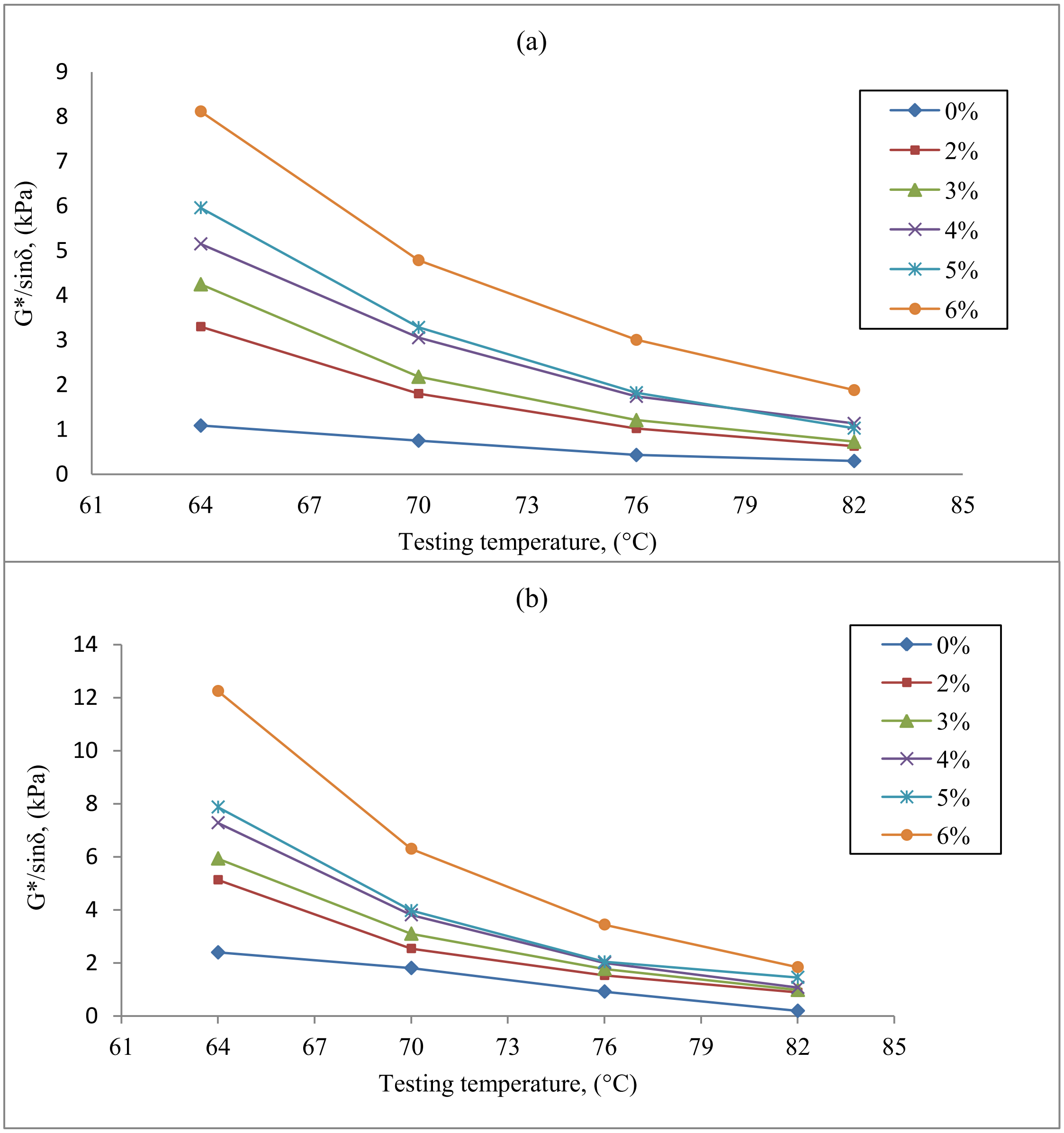


Figure 4. 1. G*/sinδ results for Ras Tannura asphalt modified by Titan 7686
(a) Original Conditions (b) RTFO residue.

4.1.2. Determination of PG's Actual grade high-service temperature

Figure 4.2 shows a sample calculation for Ras Tannura asphalt modified with 2% Titan™ 7206 polymer after short-term ageing. Figure 4.2-a shows the testing results for the original conditions while Figure 4.2-b shows the results for RTFO testing.

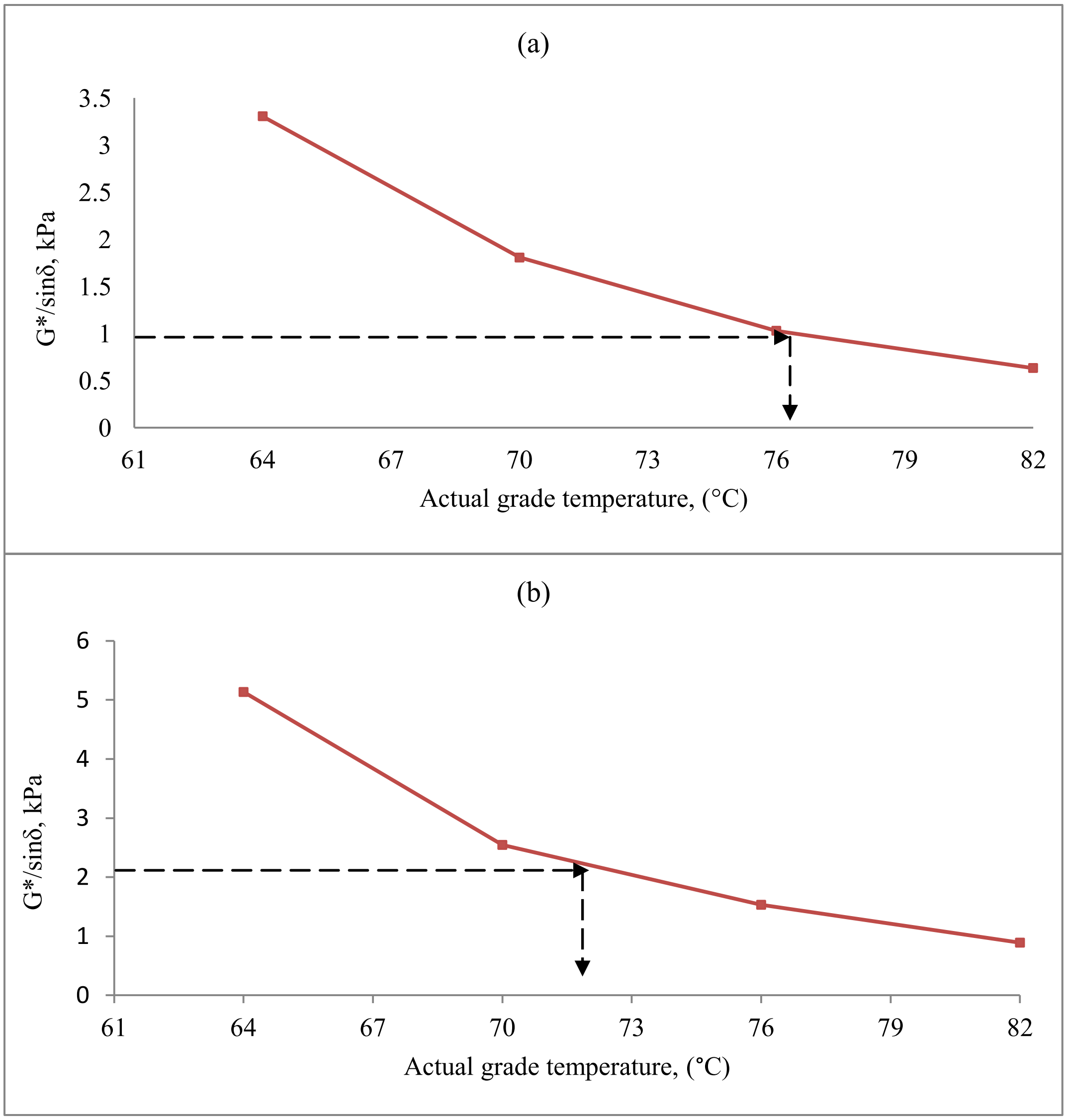


Figure 4. 2. G*/sinδ results for Ras Tannura asphalt modified by 2% Titan 7686 (a) Original Conditions (b) RTFO residue.

It can be shown from Figure 4.2-a that the Actual grade temperature is 76°C at fresh conditions and from Figure 4.2-b the actual grade temperature is 72°C. The lowest grade of the two conditions is selected to be the upper grade of that modified sample which is the 72°C. Same procedure is followed for the other samples and the results are listed in Table 4.2 below.

Table 4. 2. High-service temperature of the modified and unmodified asphalt.

Asphalt Source	% polymer	SBS	Polybilt 101	Titan 7686	Titan 7205	SBS:Titan 7686	SBS:Titan 7205
Ras Tanura	0	66.0	66.0	66.0	66.0	66.0	66.0
	2	74.2	70.9	71.9	74.3	73.8	75.3
	3	78.1	73.2	74.2	76.0	75.6	77.3
	4	81.5	75.6	77.5	77.1	76.9	79.1
	5	85.2	78.9	78.1	81.0	82.5	82.6
	6	89.3	82.1	80.3	85.7	84.7	87.6
Riyadh	0	64.2	64.2	64.2	64.2	64.2	64.2
	2	73.8	69.0	71.0	70.0	71.1	71.8
	3	79.1	72.1	72.5	74.3	75.1	75.4
	4	80.5	73.4	79.2	74.7	75.5	78.3
	5	82.8	76.4	79.7	76.0	76.5	79.6
	6	84.2	80.8	82.1	79.1	80.0	81.2
Jeddah	0	63.3	63.3	63.3	63.3	63.3	63.3
	2	69.1	64.2	70.2	73.0	69.5	70.9
	3	71.0	68.6	75.3	77.0	71.9	72.0
	4	74.7	71.2	82.4	78.1	73	73.2
	5	77.7	76.9	83.4	78.8	74.8	79.5
	6	83.9	81	85.1	82	77.8	81.3
Yanbu	0	63.2	63.2	63.2	63.2	63.2	63.2
	2	69.8	67.7	70.2	72.1	71.1	70.2
	3	72.1	70.7	74	75.8	74.0	73.9
	4	75.4	71.7	76.3	77.9	75.3	78.4
	5	79.4	75.2	81.3	79.7	75.9	78.7
	6	82.8	78.3	82.4	83.3	77.5	80.4

Table 4.1 shows the results of the actual upper actual grade temperature of performance grading system of modified binder from different sources of asphalts, where Figures 4.3 to 4.6 show graphically the results of Table 4.1.

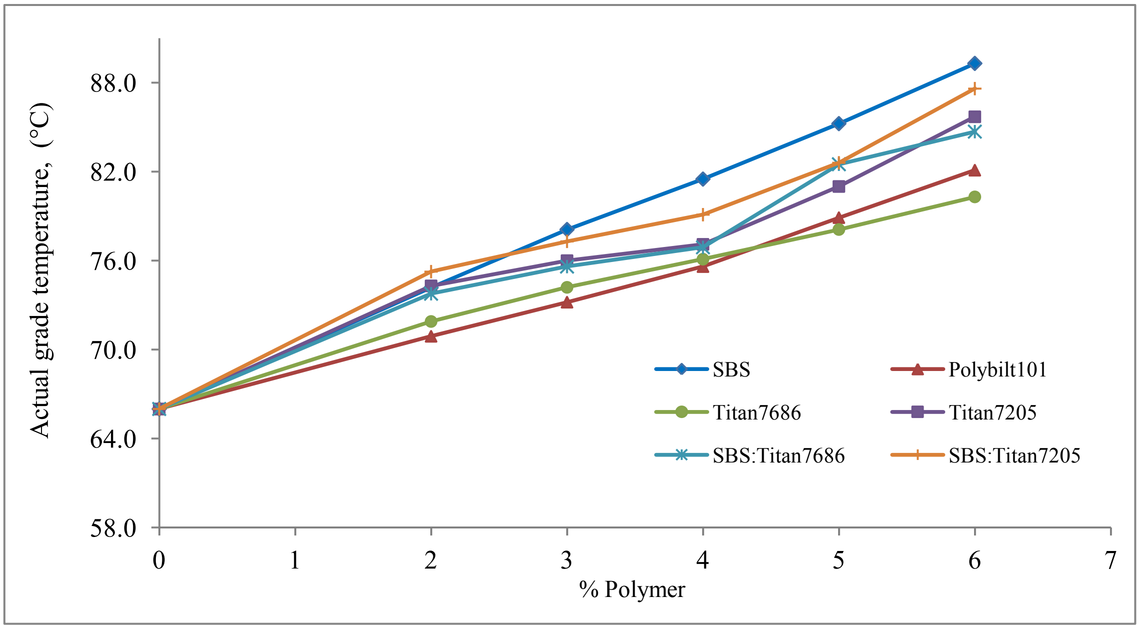


Figure 4. 3. Effect of polymers on Ras Tannura asphalts behavior.

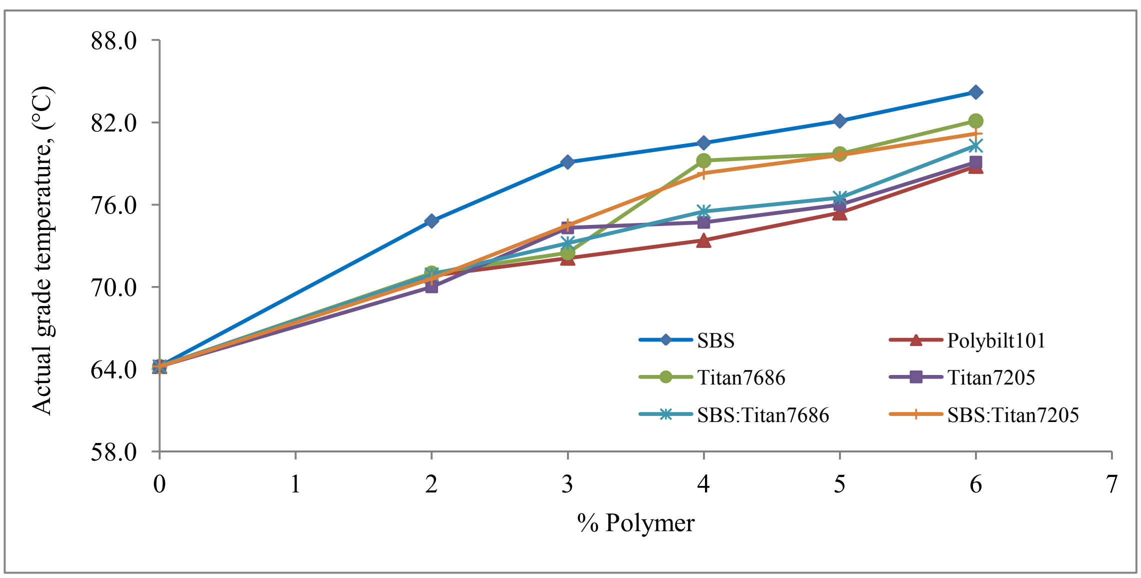


Figure 4. 4. Effect of polymers on Riyadh asphalts behavior.

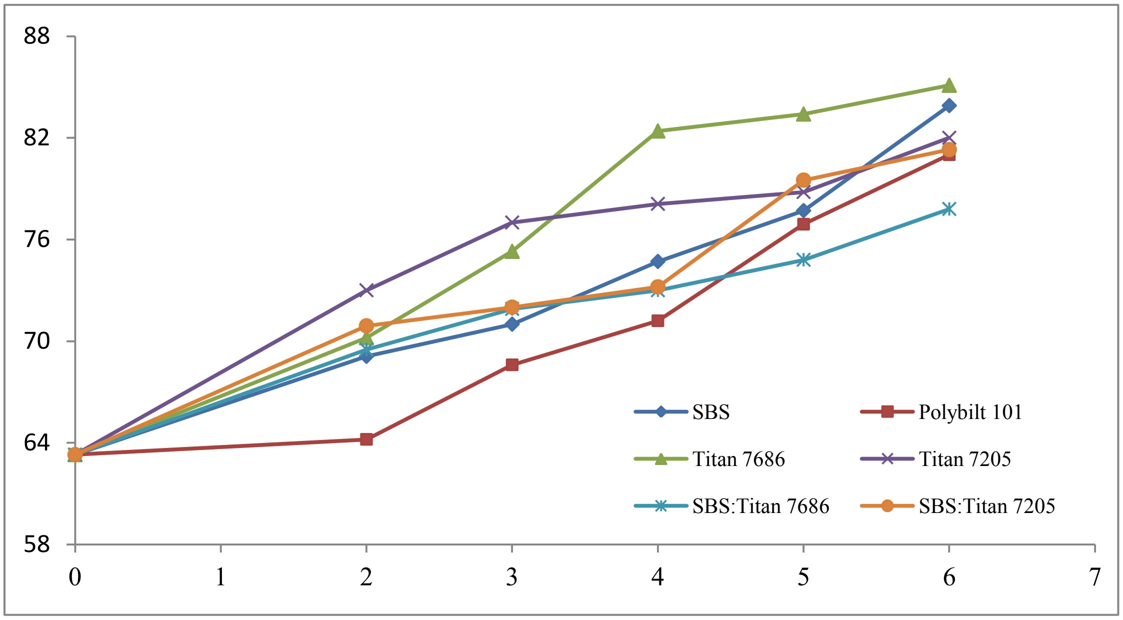


Figure 4. 5. Effect of polymers on Jeddah asphalts behavior.

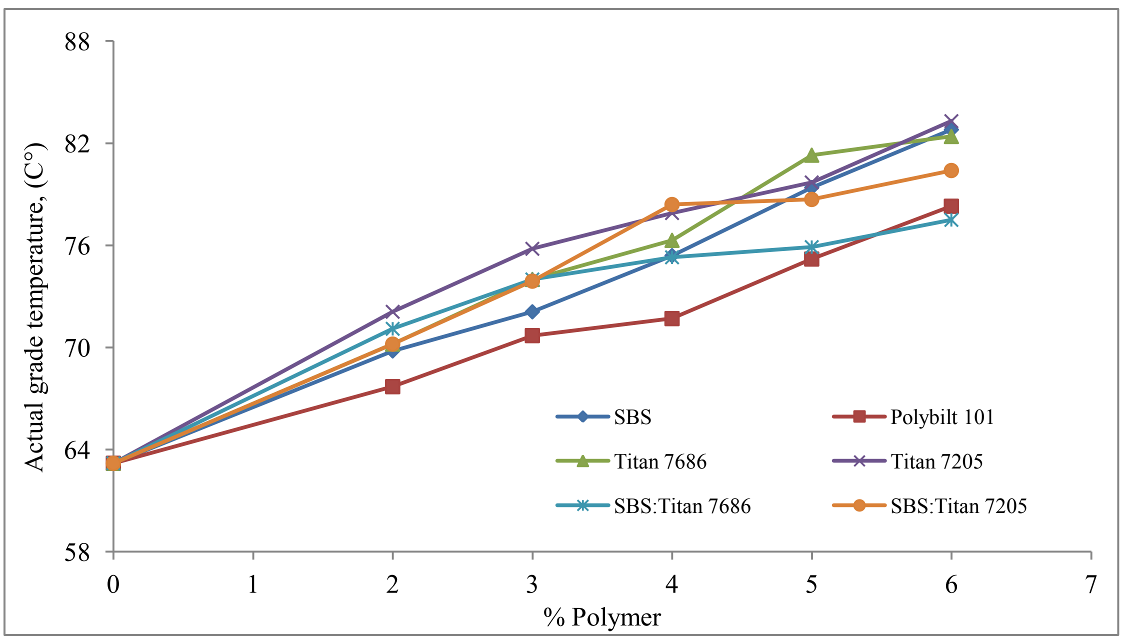


Figure 4. 6. Effect of polymers on Yanbu asphalts behavior.

From Figures 4.3 to 4.6 it can be shown that the six asphalt-polymer combinations have trends in modifying asphalt performance and resistance to high service temperatures. SBS has the best effect on improving the asphalts compared to other polymers where Polybilt 101 is the worst among these polymers.

4.1.3. Amount of polymers needed to obtain the required Performance Grade

Table 4.3 shows the amount of polymers, as a percent of binder weight, needed to increase the high service grading temperature to PG 70, PG 76 and PG 82.

Table 4. 3. Amount of polymers needed to reach required PG

	PG 70	**PG 76**	**PG 82**
SBS	1.6	3.34	5.1
Polybilt	2.48	4.7	6.92
Titan 7686	1.72	3.61	5.49
Titan 7205	1.59	3.65	5.72

SBS polymer shows a remarkable performance as compared with others, all the PG Actual grade temperatures depends on the elastic and viscosity of the asphalts termed by ($G^*/\sin\delta$). For this reason, SBS as elastomers has best improvement of the tested samples. On the other hand, Polybilt is the least effective polymer and has the least elastomeric characteristics among other polymers, even when compared to Titans polymers.

4.1.4. Effect of polymer type and amount on Arabian Asphalts

Each of the four types of studied polymers, namely; SBS, Titan 7686, Titan 7205 and Polybilt, was analyzed separately and its effect on performance was observed. SPSS software was used to develop a linear regression model to estimate the PG temperature from the independent variables; percent polymer and source of asphalt binders. Results are graphically shown in Figures 4.7 to 4.10.

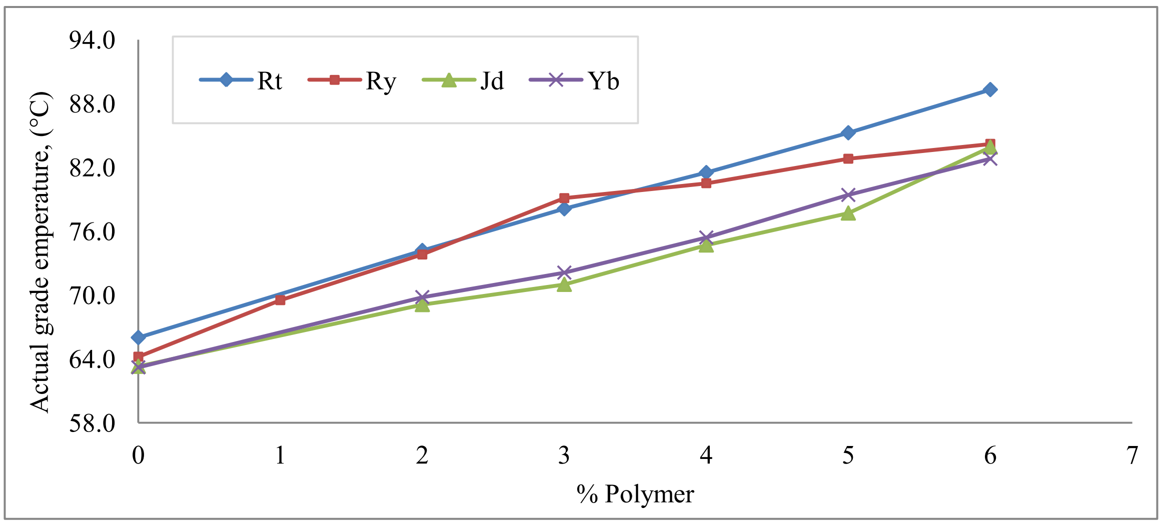


Figure 4. 7. SBS effect on PG of Saudi Arabian Asphalt

Ras Tannura asphalts show the best compatibility relation with SBS polymer. This modified binder is the highest in resisting rutting and have PG 88-16, followed by Riyadh asphalt then Jeddah and Yanbu asphalts which have PG 82-16.

The result of regression is shown in equation 4.1. The PG temperature depends on %SBS and Refinery source. The equation is:

$$\mathbf{PG_{SBS}} = 69.49 + 3.412\ (\mathbf{P}_{\mathrm{SBS}}) - 2\mathbf{R} \qquad (4.1)$$

Where PG_{SBS} is the actual grade temperature of SBS modified asphalt binders, P_{SBS} is the percent of SBS polymer added and R is a dummy variable for the Refinery as the asphalt source which takes the values of (1) for Ras Tannura asphalts, (2) for Riyadh asphalts, (3) for Jeddah asphalts and (4) is for Yanbu asphalts.

Assuming confidence level $\boldsymbol{\alpha} = 0.05$, statistical model was generated and summarized in Table 4.4. This model has a high value of $\mathbf{R^2}$ which equals to 0.957 which is close to 1.00 and low value of Standard error of the estimate and equals to 1.614. Finally, Durbin-Watson (D) equal to 0.891 which is less than d_L= 1.29 and more than 0. This can lead to the conclusion that there is a significant autocorrelation between variables.

Table 4. 4. Model Summary of SBS polymer PG of asphalt binders.

Mode	R	R^2	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	0.978	0.957	0.953	1.61475	0.891

Analysis of Variance for the whole model is shown in Table 4.5 below. The results of F-test for the overall model show significant p-value (0.0003) which is less than 0.05 which indicates that the model can be used to predict the PG (actual grade temperature) from the explanatory variables (Polymer type, polymer amount and asphalt source).

Table 4. 5. Analysis Of Variance for the PG_{SBS} model

Model	Sum of Squares	Df	Mean Square	F	Sig.
Regression	1208.330	2	604.165	231.710	0.000
Residual	54.756	21	2.607		
Total	1263.086	23			

The t-test shows the significance of each coefficient used in the model and shown in Table 4.6.

Table 4. 6. Regression Coefficients of the PG_{SBS} model

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	69.489	0.981		70.839	0.0000
P	3.416	0.167	0.929	20.436	0.0000
R	-1.995	0.295	-0.307	-6.767	0.000001

The results of t-test show that each of the independent variables (i.e. %polymer and Refinery) has a significant effect in predicting the dependent variable because they have a p-value less than 0.05. Similar analysis was conducted for the other polymers and the results are shown in the following pages.

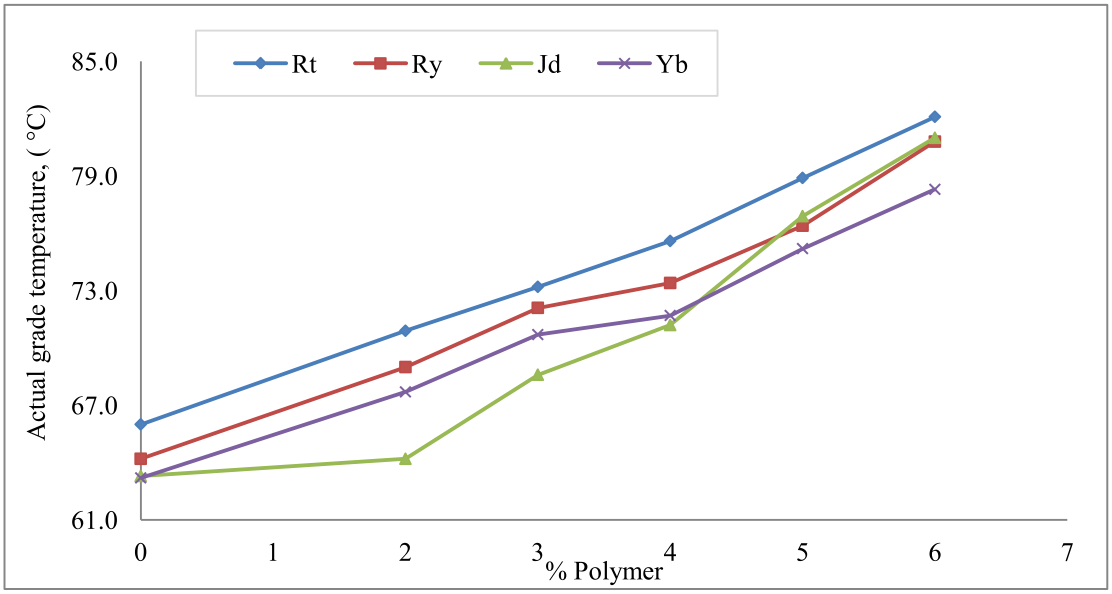


Figure 4. 8. Polybilt 101 effect on PG of Arabian Asphalt

$$\mathbf{PG_{Pb}} = 66.165 + 2.713\ (\mathbf{P}_{Pb}) - 1.173\mathbf{R} \tag{4.2}$$

Equation 4.2 shows the results of a regression model to predict the PG value at given percent of Polybilt and specific asphalt source. Comparison between equation 4.2 and 4.1 indicated that 1% of SBS increases 3.412 degrees of actual temperature while 1% of Polybilt increases the PG by only 2.713 degrees.

Table 4.7, 4.8 and 4.9 show statistical analysis results of the model indicated in equation 4.2. Table 4.7 shows that R^2 equals to 0.946 and Tables 4.8 and 4.9 show low p-values for F-test and t-test (p-value < 0.05).

Table 4. 7. Model Summary of Pb polymer PG of asphalt binders

Model	R	R^2	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	0.973	0.946	0.941	1.40082	1.110

Table 4. 8. Analysis of Variance for the PG_{Pb} model

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	728.197	2	364.098	185.547	0.000
Residual	41.208	21	1.962		
Total	769.405	23			

Table 4. 9. Regression Coefficients of the PG_{Pb} model

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	66.165	0.851		77.751	0.000
P	2.713	0.145	0.945	18.710	0.000
R	-1.17	0.256	-0.232	-4.588	0.000

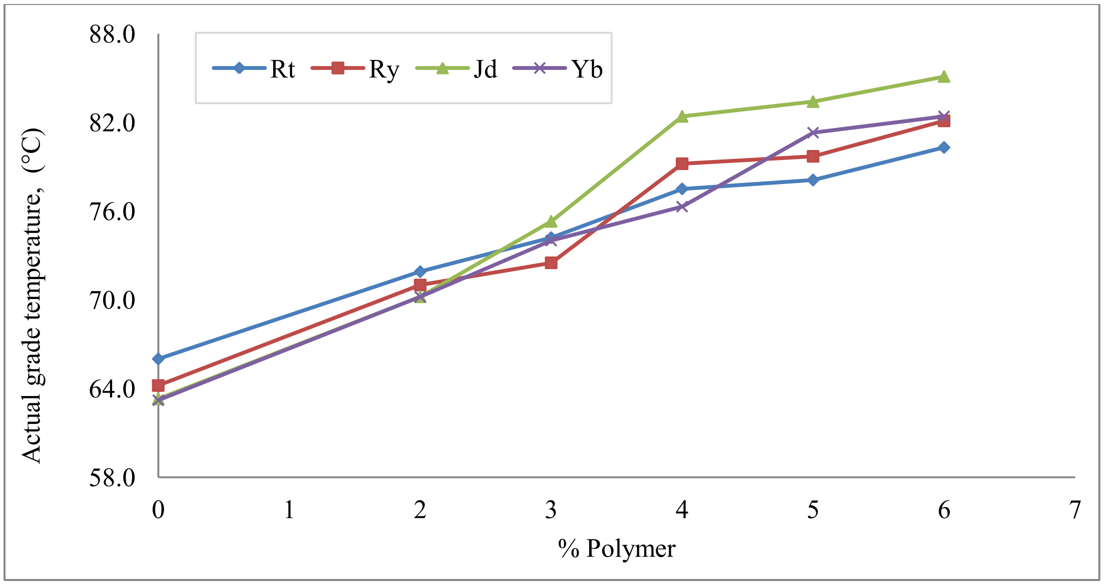


Figure 4. 9. Titan 7686 effect on PG of Arabian Asphalts.

$$\mathbf{PG_{T6}} = 3.165\ \mathbf{P}_{T6} + 64.224 \tag{4.3}$$

This model has good R^2 value of (0.926) and low standard error of the Estimate (1.88). Furthermore, the p-value of F-test and t-test are very close to 0.00 which indicates that the model is significantly predicting the PG_{T6}.

However, the effect of asphalt source which indicated in **R** independent variable is not showing significance because the value of p-value shown in Table 4.12 is 0.66 and greater than 0.05.

Table 4. 10. Model Summary of Titan 7686 polymer PG of asphalt binders

Model	R	R^2	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	0.962	0.926	0.919	1.88403	1.129

Table 4. 11. Analysis of Variance for the PG_{T6} model

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	935.857	2	467.929	131.827	0.000
Residual	74.541	21	3.550		
Total	1010.398	23			

Table 4. 12. Regression Coefficients of the PG_{T6} model

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	64.224	1.145		56.113	0.000
P	3.165	0.195	0.962	16.231	0.000
R	.153	0.344	0.026	0.446	0.660

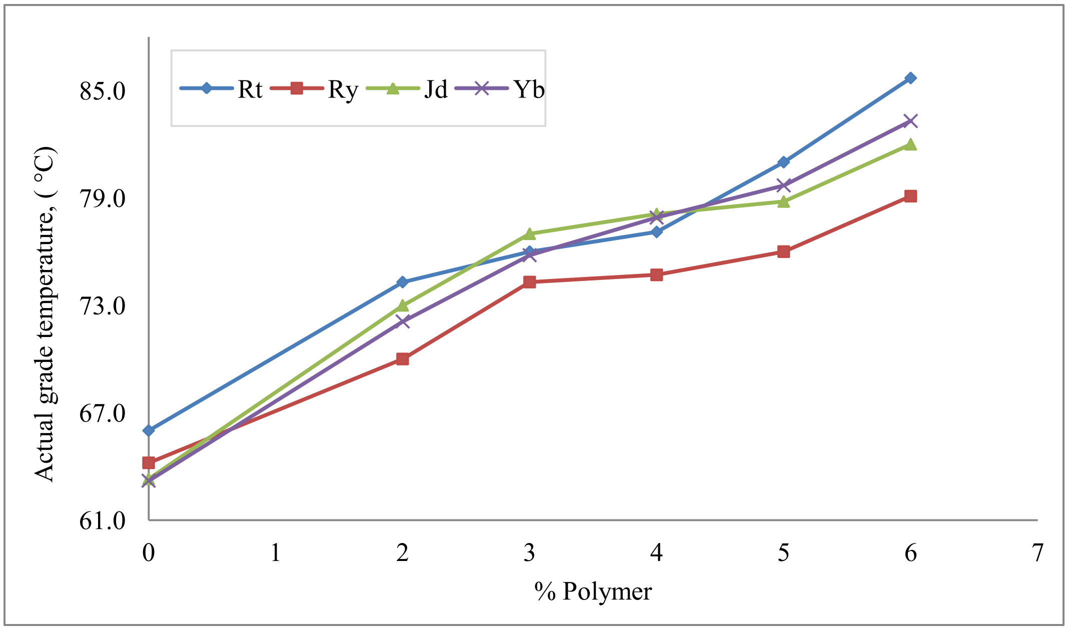


Figure 4. 10. Titan 7205 effect on PG of Arabian Asphalt.

$$\mathbf{PG_{T5}} = 2.879\ \mathbf{P}_{T5} + 65.94 \quad (4.4)$$

This model has good R^2 value of (0.898) and low standard error of the Estimate (2.048). Furthermore, the p-value of F-test and t-test are very close to 0.00 which indicates that the model is significantly predicting the PG_{T5}.

However, the effect of asphalt source which indicated in **R** independent variable is not showing significance because the value of p-value shown in Table 4.15 is 0.648 and greater than 0.05.

Table 4. 13. Model Summary of Titan 7205 polymer PG of asphalt binders

Model	R	R^2	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	0.948	0.898	0.888	2.04819	0.961

Table 4. 14. Analysis of Variance for the PG_{T5} model

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	774.661	2	387.331	92.329	0.000
Residual	88.097	21	4.195		
Total	862.758	23			

Table 4. 15. Regression Coefficients of the PG_{T5} model

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	65.944	1.244		52.999	0.000
P	2.879	0.212	0.947	13.581	0.000
R	-0.173	0.374	-0.032	-0.464	0.648

Figure 4.11 presents the bar chart to compare the effect of polymer type on modifying the performance of asphalt from different sources.

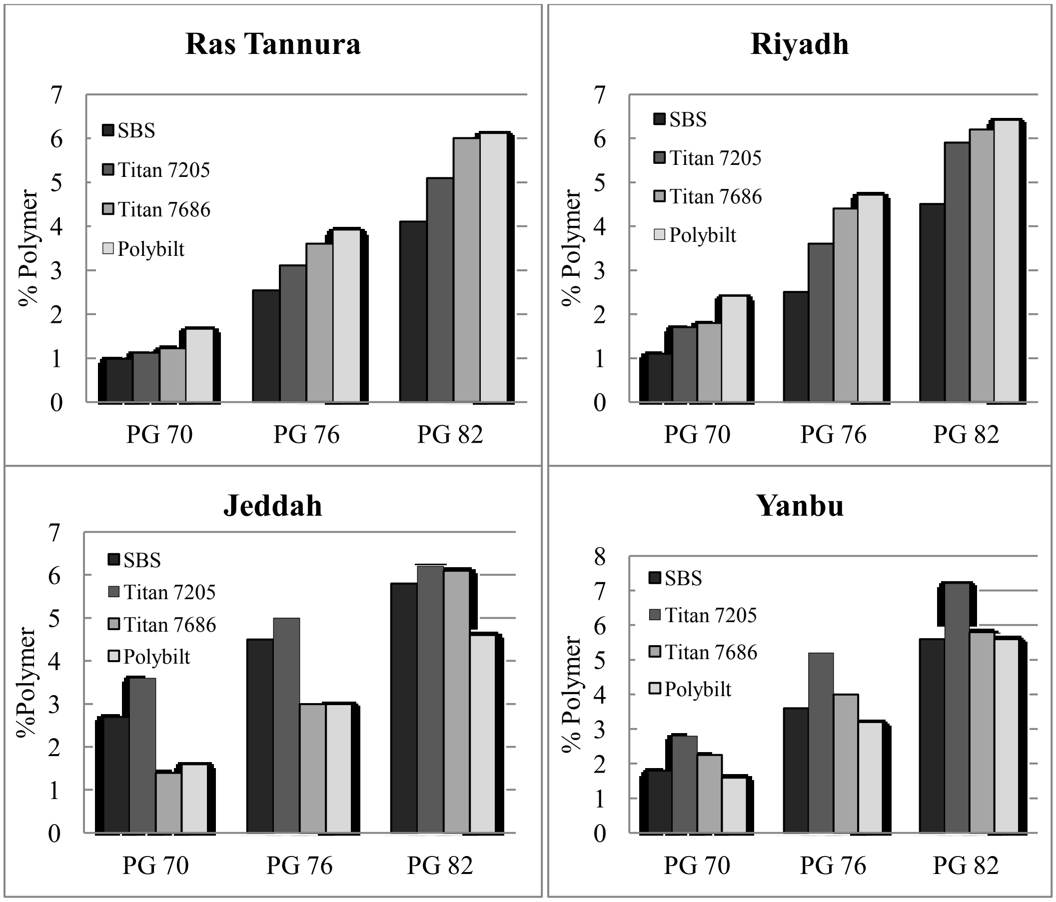


Figure 4. 11. Amount of polymer needed to achieve the required PG.

It is shown from the above Figure that for Ras Tannura, Riyadh and Yanbu, SBS has the best effect and thus less amount of polymer is needed for the required improvement. While Polybilt 101 is comparatively has the least effect, Titan polymers effect is greater than Pb and less than that of SBS.

4.1.5. Final Model to predict the PG as a function of polymer

After combining the results of each modified sample from four refineries and four polymers as shown in Table 4.2, a linear regression model can be used to predict the actual performance temperature as a dependent variable. The independent variables are: percent polymer (as binder weight), source of asphalt and polymer type. Tables 4.16, 4.17 and 4.18 show the analysis of the results using SPSS software.

Table 4. 16. Model Summary of Titan 7205 polymer PG of asphalt binders

Model	R	R^2	Adjusted R Square	Std. Error of the Estimate
1	0.930	0.864	0.860	2.45513

Table 4. 17. Analysis of Variance for the PG model

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	5067.968	3	1689.323	330.956	0.000
Residual	714.611	140	5.104		
Total	5782.579	143			

Table 4. 18. Regression Coefficients of the PG model

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	68.107	0.748		91.006	0.000
R	-0.974	0.168	-0.172	-5.782	0.000
P	4.235	0.668	1.318	6.337	0.000
P_{Type}	-1.498	0.772	-0.404	-1.941	0.054

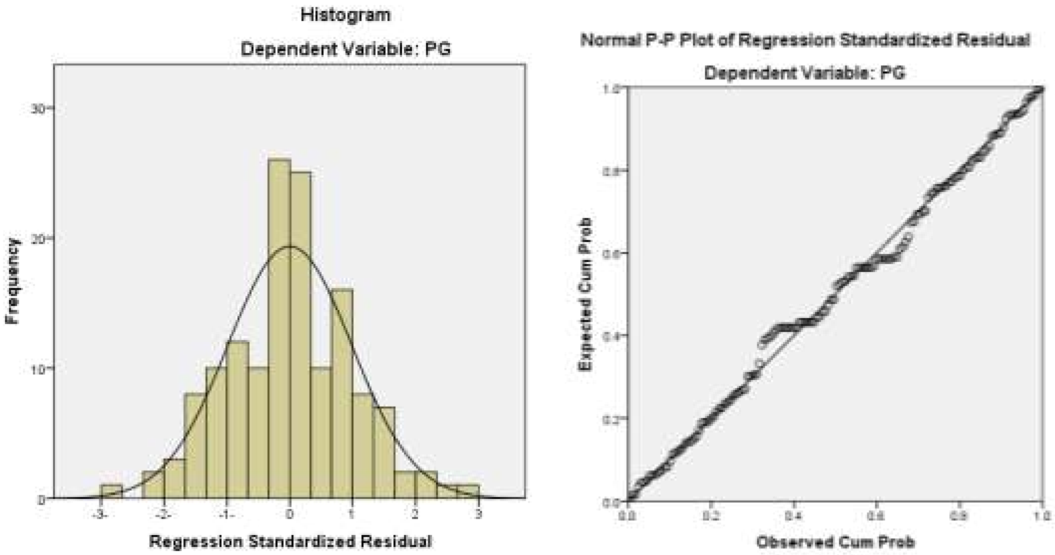


Figure 4. 12. Histogram and P-P Plot of the residuals

The histogram in Figure 4.12 supports the hypothesis of the normal distribution of the sample and the linearity of the residual in the same above emphasizes the assumption that the relation between the PG as a dependent variable and the other independent variables is linear.

F-test shown in Table 4.17 indicates that the model is significant which has p-value <0.05 in addition to t-test which shows the significance of the coefficients in the model. So the developed model is shown in equation 4.5 below.

$$\mathbf{PG} = 68.11 - 0.974\ (\mathbf{R}) + 4.23\ (\mathbf{\%P}) - 1.498\ (\mathbf{P_{type}}) \qquad (4.5)$$

Where:

PG is the actual upper temperature of the Performance Grade in °C.

R is the asphalt source (i.e Rt, Ry, Jd and Yb)

%P is percent of polymer.

$\mathbf{P_{type}}$ is the type of the polymer used in the test. (i.e.; SBS, Pb, Titan7686, Titan 7205, SBS: Titan 7686 or SBS: Titan 7205 in addition to neat asphalt).

This equation gives a good idea about the effect of polymer amount and corresponding actual grade temperature regardless of the type of polymer used. The intercept value (64.4 C°) is considered the average grade high temperature of neat asphalt of all tested samples (i.e.; all asphalt sources).

4.2. Elastic Recovery of the Modified Asphalts

As discussed previously, the conventional Elastic Recovery test was added to Superpave Performance Grade (PG) system in order to evaluate the polymer modified asphalt binders and many researchers suggested that the accepted polymer modified asphalts should have percent recovery value of more than 60%. [D' Angelo 2009 and Eileen et at 2011]

Each sample of this study was prepared and conditioned according to AASHTO T51 procedure, and subjected to elastic recovery test then recorded the percent recovery of each combination at 25°C.

Table 4.19 and Figure 4.13 show the results of Elastic Recovery test of Ras Tannura asphalt. The other refineries are shown in Appendix B.

4.2.1. Elastic Recovery evaluation of Ras Tannura Asphalts

Table 4. 19. Percent Recovery values for modified Ras Tannura Asphalts.

Additive Name	**Actual upper grade Temp.**	**True PG**	**Percent Recovery at 25°C**
None	66.0	PG 64	0.0
SBS	74.2	PG 70	55.0
	78.1	PG 76	58.2
	81.5	PG 76	60.0
	85.2	PG 82	62.0
Polybilt 101	73.2	PG 70	33.0
	75.6	PG 76	41.0
	82.1	PG 82	55.0
Titan 7686	71.2	PG 70	19.0
	74.2	PG 70	29.5
	77.5	PG 76	40.1
	86.4	PG 82	64.0
Titan 7205	74.3	PG 70	18.0
	76.0	PG 76	38.8
	77.1	PG 76	40.9
	85.7	PG 82	60.0
SBS: Titan 7686	73.8	PG 70	35.0
	77.2	PG 76	42.4
	82.5	PG 82	57.5
SBS:Titan 7205	75.3	PG 70	31.0
	79.1	PG 76	49.0
	82.6	PG 82	58.0

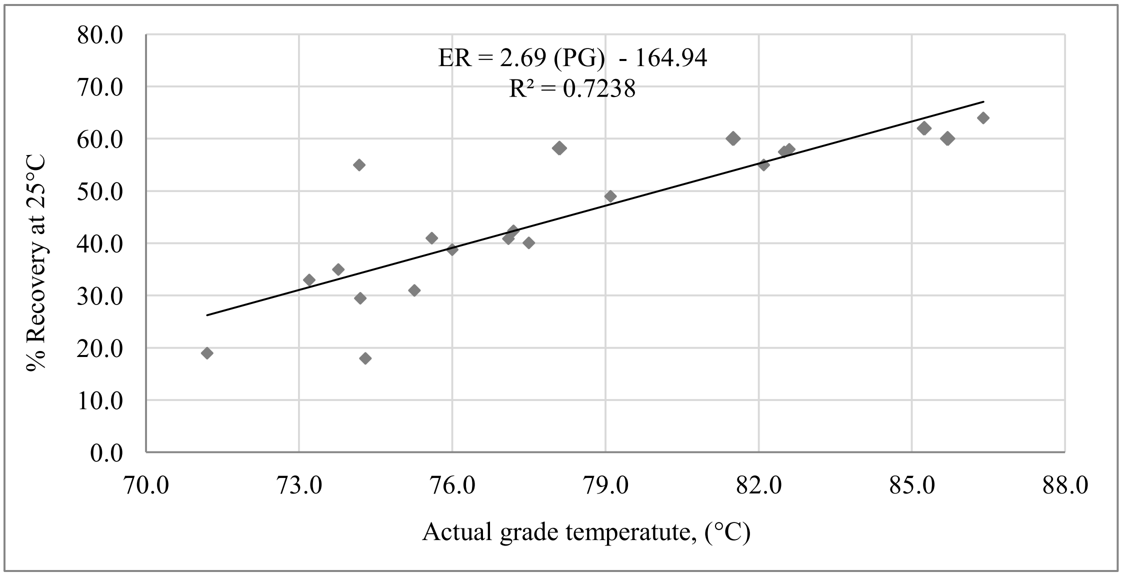


Figure 4. 13. Elastic Recovery behavior of Ras Tannura Asphalts.

Figure 4.13 shows that there is a linear relation between the actual upper grade temperature and the elastic recovery with good R^2 value of 0.7238 and standard deviation of ±14.146%. For SBS modified samples, 2% of polymer resulted in 55% recovery while 6% of Pb was needed to reach the same percent recovery. Same analysis was done for the other three asphalt sources and presented in Appendix B.

4.2.2. Elastic Recovery evaluation of Arabian Asphalt.

When combining the asphalts altogether to find the effect of polymers in improving the elastic recovery of Arabian asphalts, a good correlation found between performance grade of the tested samples and percent recovery at 25°C. Figure 4.14 shows the relation between the actual grade temperature of PG and the % elastic recovery.

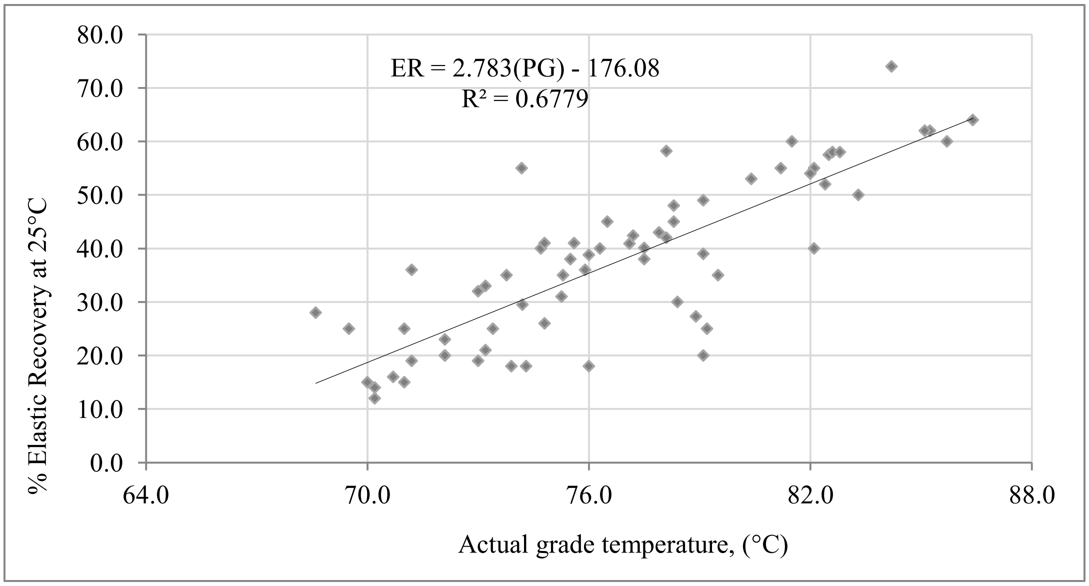


Figure 4. 14. Elastic Recovery behavior of the Arabian Asphalts.

The statistical model used to express the relation between the actual grade temperature and the percent recovery of asphalt samples modified with any type of polymers. The model has R^2 of 0.678 and standard deviation of ±15.2%.

$$\mathbf{ER} = 2.783\ \mathbf{PG} - 176.08 \tag{4.6}$$

Where:

ER is the % Recovery at 25°C and

PG is the corresponding actual upper grade temperature.

The correlation between PG and ER is not affected by source of asphalt binders, because each asphalt-polymer combinations have been characterized by their performance against temperature and assigned a PG value. So, the model is covering all asphalt samples that have been tested.

4.3. Multiple Stress Creep Recovery (MSCR) Test

The MSCR Recovery test is intended to replace any current PG Plus tests now in use like the Elastic Recovery to evaluate the presence of polymers in modified binders, not as an additional test. Asphalt Institute suggests that this test should be used for evaluation of any polymer modified asphalt by testing samples prepared from RTFO residue. And it also recommends testing at 64°C at two stress levels; 100 Pa and 3200 Pa and following the AASHTO TP 70.

All samples in the experimental program have been tested using MSCR procedure that uses the DSR machine. The stress levels used are 0.1 kPa and 3.2 kPa. The creep portion of the test lasts for 1 second, which is followed by a 9-second recovery. Ten creep and recovery cycles are used at each stress level. The average values of the creep and recovery start and end points were determined to calculate the percent recoverable strain at the two stress levels in addition to the non-recoverable compliance Jnr.

4.3.1. Determination of percent recovery (%R) and non-recoverable compliance (Jnr)

Figures 4.15 shows the results of testing Riyadh asphalt sample modified with 5% SBS at 3.2 kPa stress level. It can be shown from the Figures that at 0.1 kPa stress level the recoverable strain are 70% at 3.2 kPa.

Tables 4.20 and 4.21 show the results of MSCR test at the two stress levels and Figures 4.16 to 4.19 show the graphical relation between the actual grade temperature and the MSCR parameters. Other results are shown Appendix B.

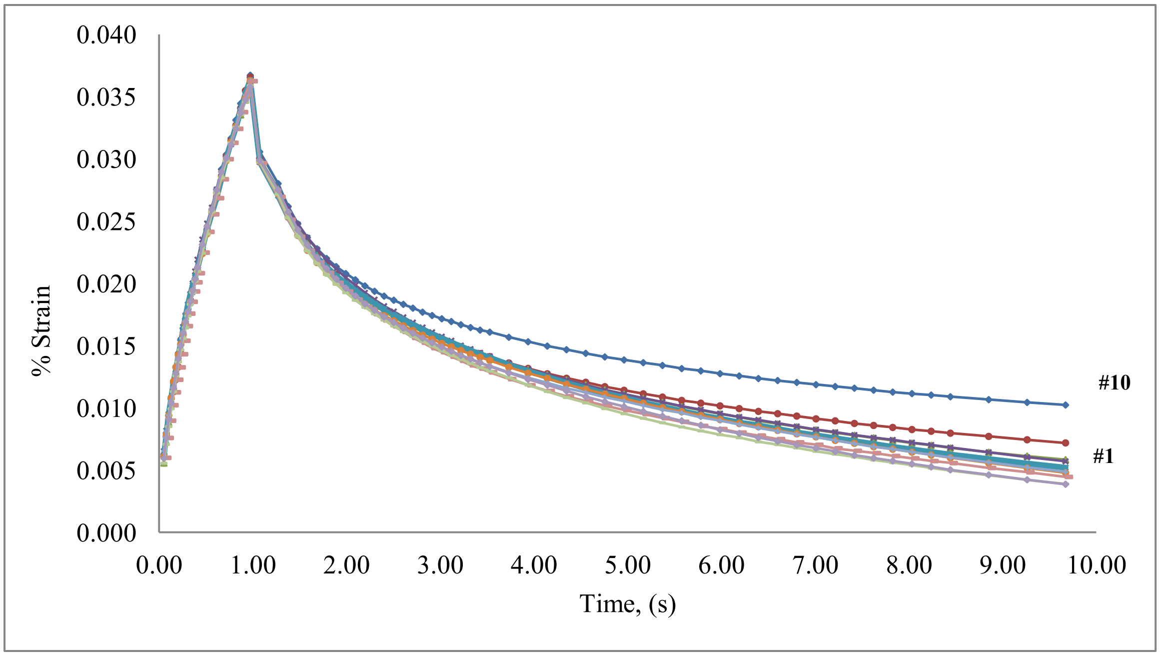


Figure 4. 15. MSCR test of Riyadh asphalt modified with 5% SBS and tested under 0.10 kPa stress

Figure 4.15 shows ten cycles of creep and recovery test, a portion of the applied stress is reduced by the rheological properties of the asphalt as a viscoelastic material. In most cases, some portions of the strain will not recover causing plastic deformations which lead to excessive rutting. For this reason, asphalt should be modified with suitable elastomeric polymers to improve elasticity.

4.3.2. MSCR parameters for Ras Tannura Asphalts

MSCR parameters indicate the %recovery and non-recoverable compliance at two stress levels, 0.1 kPa and 3.2 kPa. Table 4.20 shows the final results of these parameters corresponding to PG temperature. Figure 4.16 shows the relationship between actual grade temperature and percent recovery at the 0.1 kPa stress level, while Figure 4.17 shows the Jnr values. The same relation is shown in Figures 4.18 and 4.19 but using the 3.2 kPa stress.

Table 4. 20. MSCR results for Ras Tannura modified asphalts

Additive	% of additive	Actual Upper grade Temp.	True PG	MSCR @ 64°C			
				100 Pa		3200 Pa	
				% $R_{0.1}$	Jnr $_{0.1}$ (Kpa^{-1})	% $R_{3.2}$	Jnr $_{3.2}$ (Kpa^{-1})
None	0	64.2	PG 64	0.0	0.00	0.0	0.0
SBS	1%	69.5	PG 70	5.7	1.60	0.7	1.80
	3%	79.1	PG 76	23.9	0.27	20.9	0.3
	5%	84.2	PG 82	62.5	0.29	55.8	0.4
Pb 101	3%	72.1	PG 70	48.5	0.49	6.0	1.1
	4%	73.4	PG 70	52.0	0.35	7.0	0.80
Titan 7686	2%	71.0	PG 70	18.5	1.070	2.8	1.50
	4%	79.2	PG 76	87.5	0.062	19.5	0.80
	6%	82.1	PG 82	90.0	0.028	16.8	0.60
Titan 7205	2%	70.0	PG 70	27.1	1.14	0.3	2.2
	5%	76.0	PG 76	85.2	0.15	3.5	0.8
	6%	79.1	PG 76	68.0	0.21	9.3	0.90
SBS: Titan 7686	4%	75.5	PG 76	41.0	0.43	18.0	0.7
	5%	76.5	PG 76	34.8	0.39	14.0	0.6
SBS:Titan 7205	2%	74.8	PG 70	9.8	0.81	4.8	0.9
	4%	78.3	PG 76	34.0	0.63	11.1	1.0
	6%	81.2	PG 76	41.9	0.32	19.6	0.5

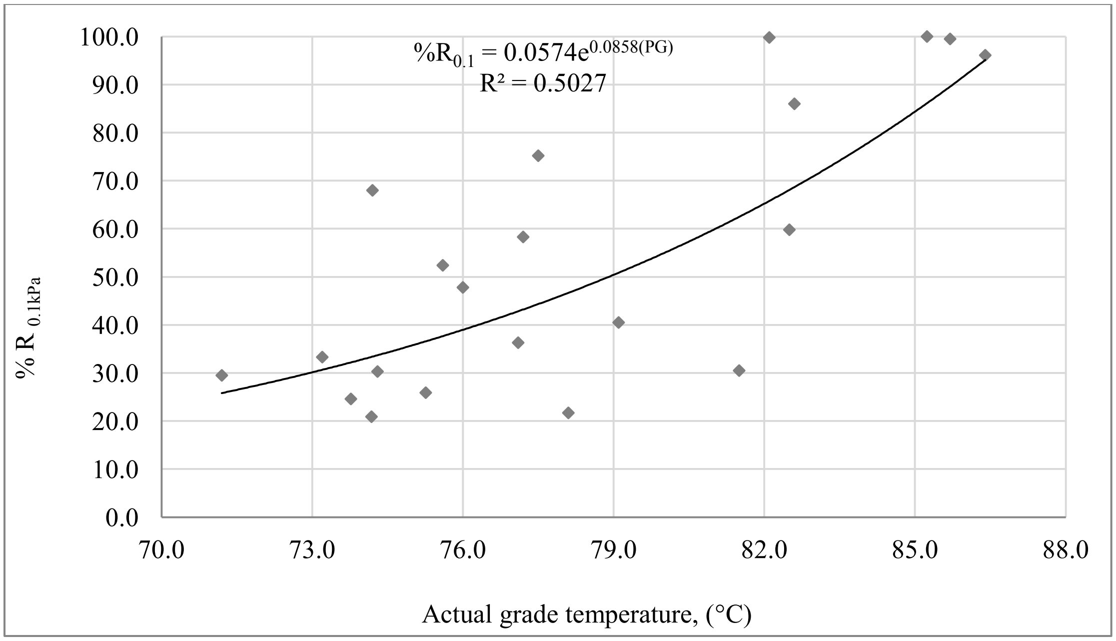


Figure 4. 16. Percent recovery results for Ras Tannura asphalts at 0.1 kPa.

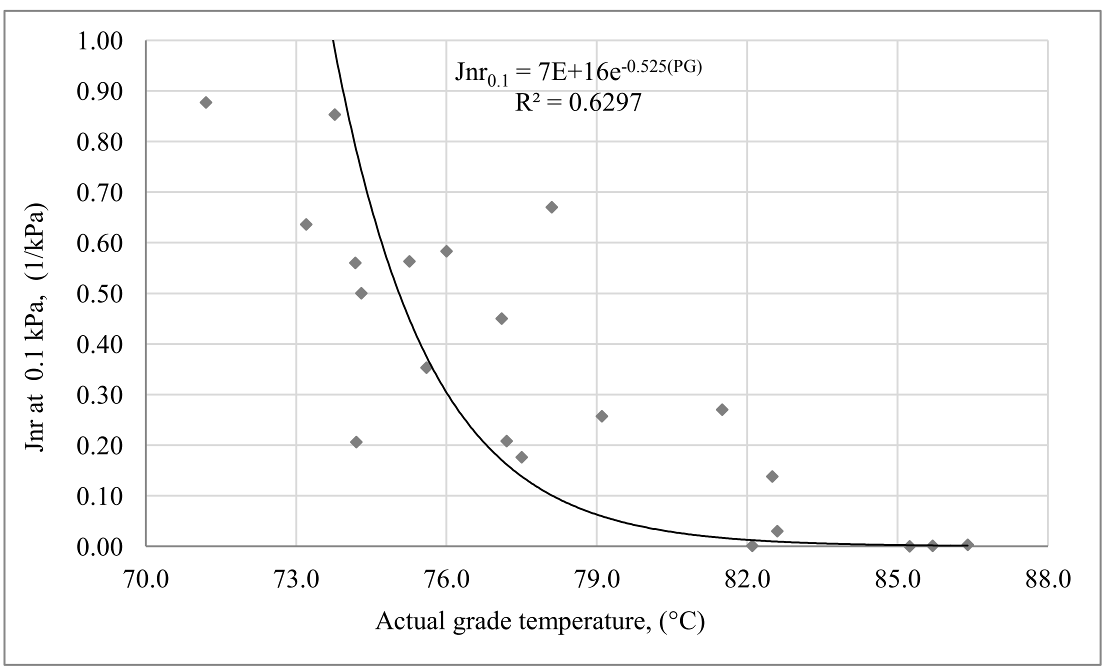


Figure 4. 17. Jnr results for Ras Tannura asphalts at 0.1 kPa.

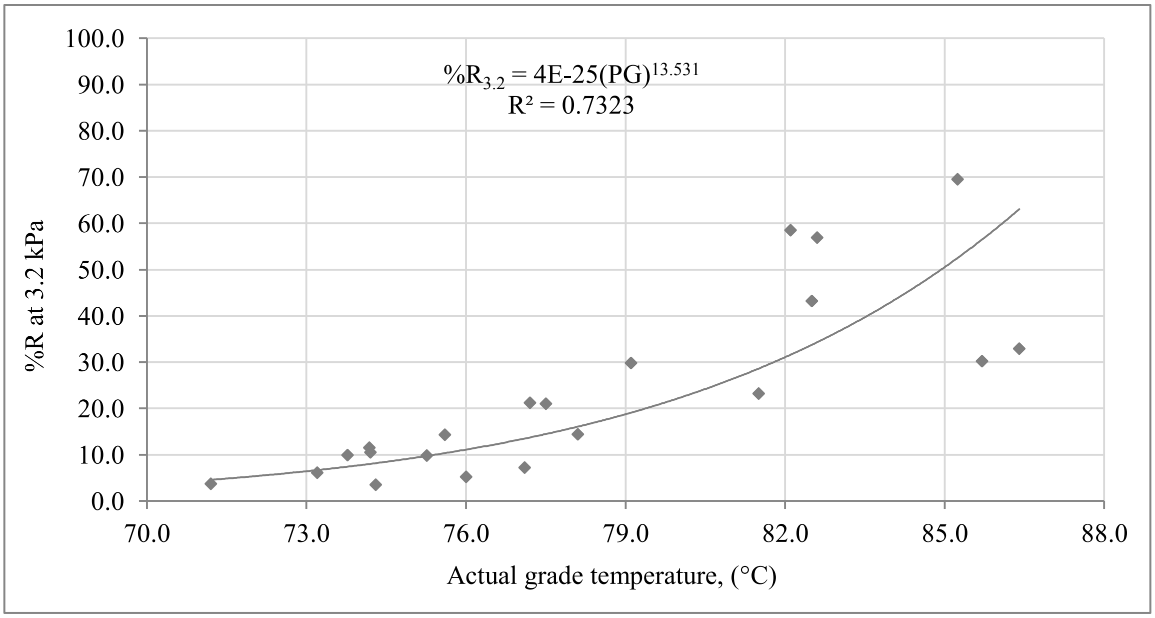


Figure 4. 18. Percent recovery at 3.2 kPa per each grade temperature for Ras Tannura asphalts.

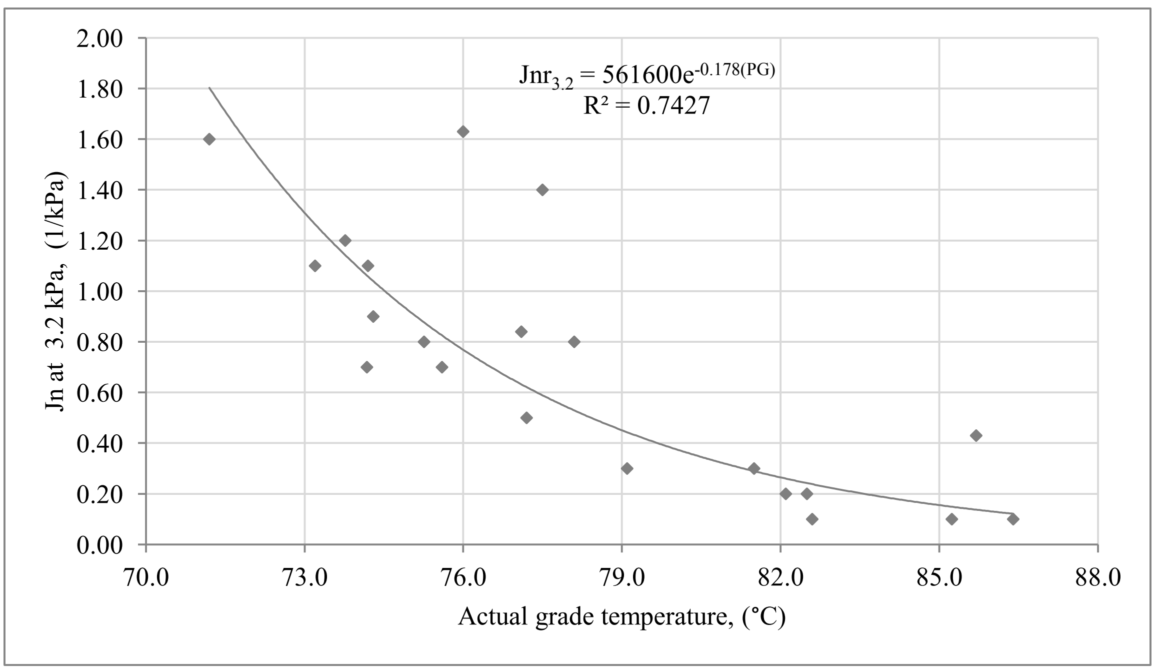


Figure 4. 19. Jnr at 3.2 kPa per each grade temperature for Ras Tannura asphalts.

Similar calculations, tables and graphical presentations of the other three refineries (i.e. Riyadh, Jeddah and Yanbu) are listed in Appendix C. However, there is no exact value accepted by AASHTO for evaluation of polymer modified asphalts using MSCR test, but many asphalt agencies and researchers studied the MSCR recommended values of percent recovery (%R) and non-recoverable compliance (Jnr).

One of the most important studies conducted by John A. D' Angelo [2009], recommend specific values of % recovery for the MSCR test, he suggested value of 20% to be the minimum accepted for polymer modified asphalt at 3.2 kPa stress.

The value of percent recovery (%R) and Non-recoverable compliance (Jnr) from MSCR test depend on both the stress level for the creep portion and actual actual grade temperature of asphalt binders (which is characterized by the type of polymer, amount of polymer and source of asphalt).

4.3.3. General relationship between actual PG temperature and MSCR parameters

It is important to evaluate the general relationship between actual grading temperature with both percent recovery (%R) and non-recoverable compliance (Jnr) values at different stress levels. This relationship includes all selected samples with different asphalt source and polymer type. Figure 4.20 shows the relationship between actual grade temperature and percent recovery. Figure 4.21 shows relationship between actual temperature and Jnr at 3.2 kPa stress level.

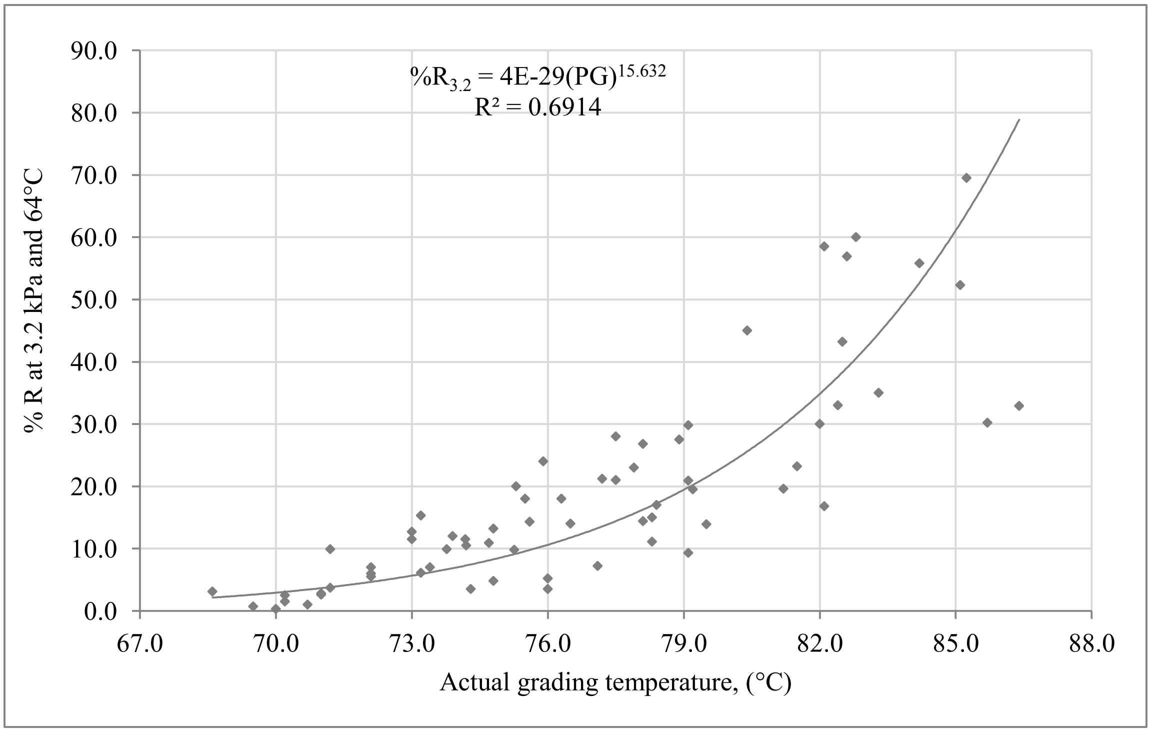


Figure 4. 20. Relationship between actual grade temperature and %R at 3.2 kPa stress.

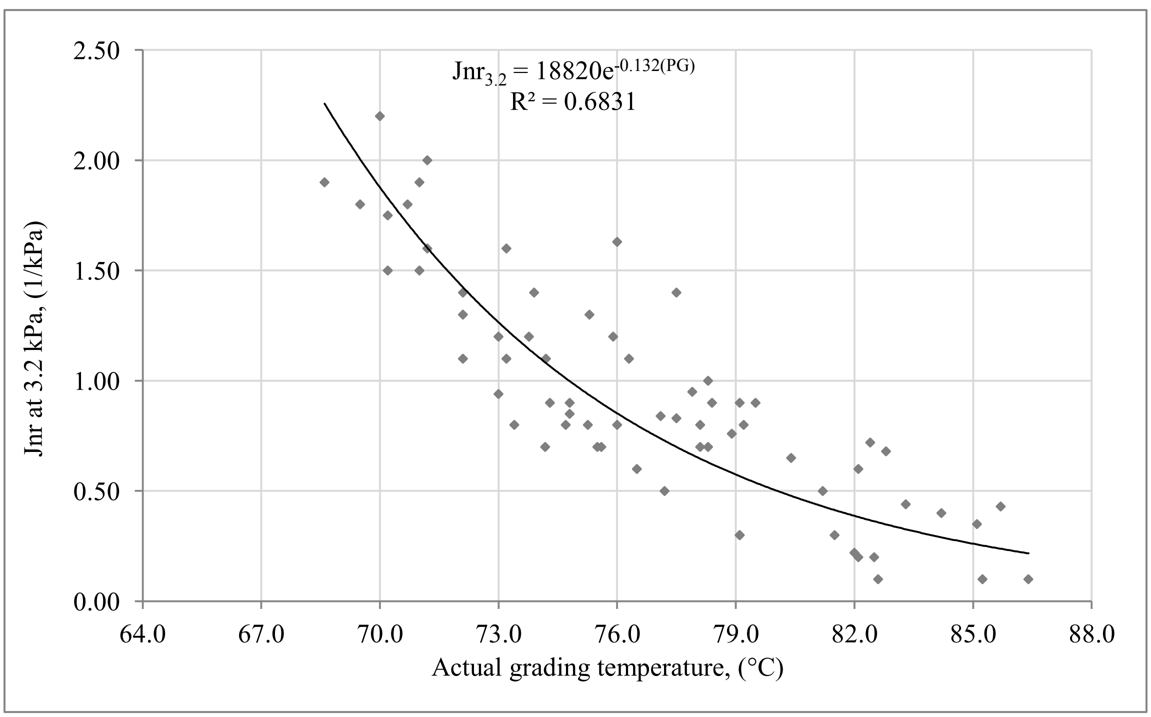


Figure 4. 21. Relationship between temperature and Jnr at 3.2 kPa stress.

AASHTO TP 70 states that if the percent recovery plots above the line (defined by the equation $y = 29.37(x)^{-0.263}$, where x = average Jnr at 3.2 kPa and y = percent recovery), the binder is modified with an acceptable elastomeric polymer. A system of "pass/fail" to be considered like the one specified in AASHTO TP 70, or for setting a minimum acceptable percent recovery. Figure 4.22 shows the recommended curve with pass/fail system.

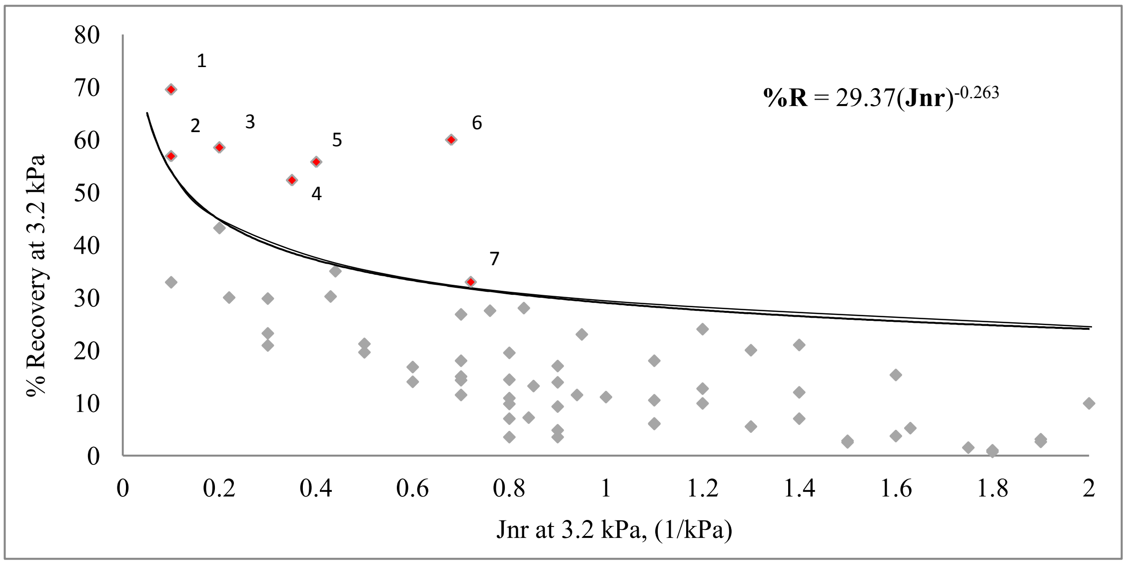


Figure 4. 22. Failing/passing system of all tested MSCR samples.

As shown from Figure 4.22, seven samples have passed the criteria of %R against Jnr relationship adopted by the FHWA. The detailed descriptions of these samples are:

1: Ras Tannura asphalt modified with SBS and has PG of 82

2: Ras Tannura asphalt modified with SBS: Titan 7205 and has PG 82

3: Ras Tannura asphalt modified with Polybilt 101 and has PG 82

4: Riyadh asphalt modified with SBS and has PG 82

5: Jeddah asphalt modified with Titan 7686 and has PG 82

6: Yanbu asphalt modified with Titan 7686 and has PG 82

7: Yanbu asphalt modified with SBS and has PG 82

There are seven polymer modified asphalts that passed the standard requirements of percent recovery (%R) and non-recoverable compliance (Jnr) relationship shown in Figure 4.22. Only PG 82-16 modified samples passed the requirements. This means that PG 82-16 is required to resist rutting while samples which have PG 76 and PG 70 are still used in order to meet temperature zoning requirements.

When studying the effect of each asphalt source, it is necessary to notice the behavior of each asphalt source. Figures 4.23 and 4.24 show the relationship between source of asphalt binder and the MSCR percent recovery and non-recoverable strain compliance.

Figures 4.23 and 4.24 show the effect of asphalt source on percent recovery values at 3.2 kPa and Jnr at the same stress level, respectively. Figure 4.25 shows the effect of asphalt source and polymer type and amount in improving the recovery characteristics of the modified asphalts.

Ras Tannura asphalt shows best performance in terms of recoverable strain and non-recoverable compliance criteria at higher stress levels. On the other hand, Riyadh and Jeddah asphalts have similar behavior in recovering the applied multiple creep stress. Yanbu asphalt shows the worst case among others.

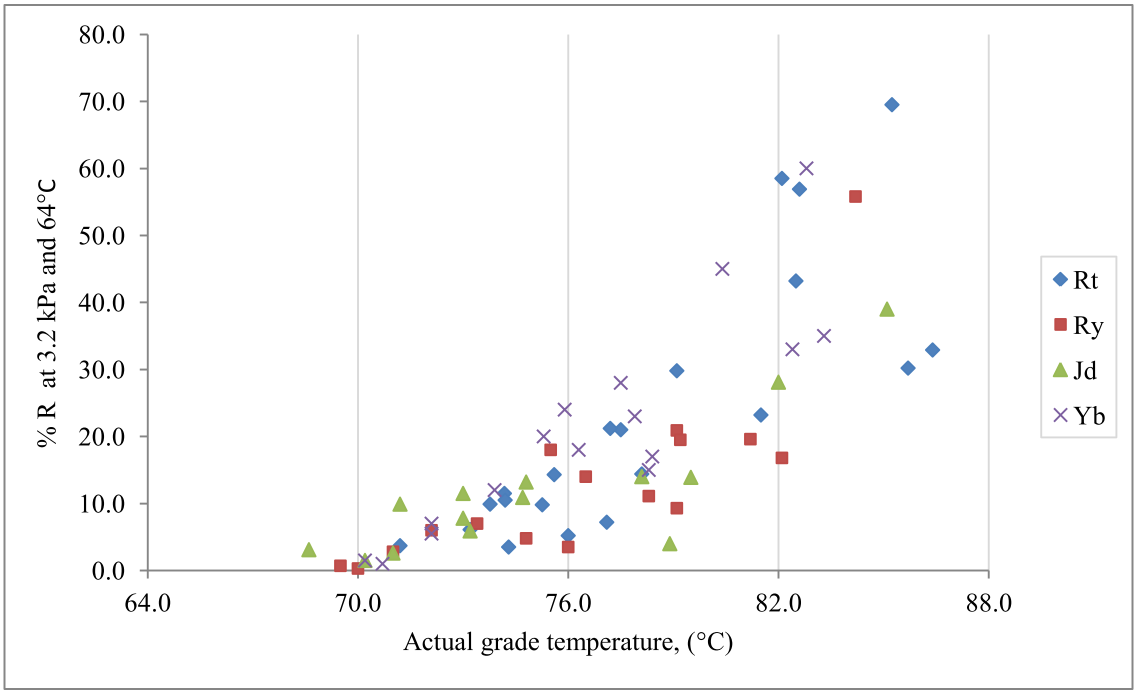


Figure 4. 23. Effect of asphalt source on percent recovery values at 3.2 kPa.

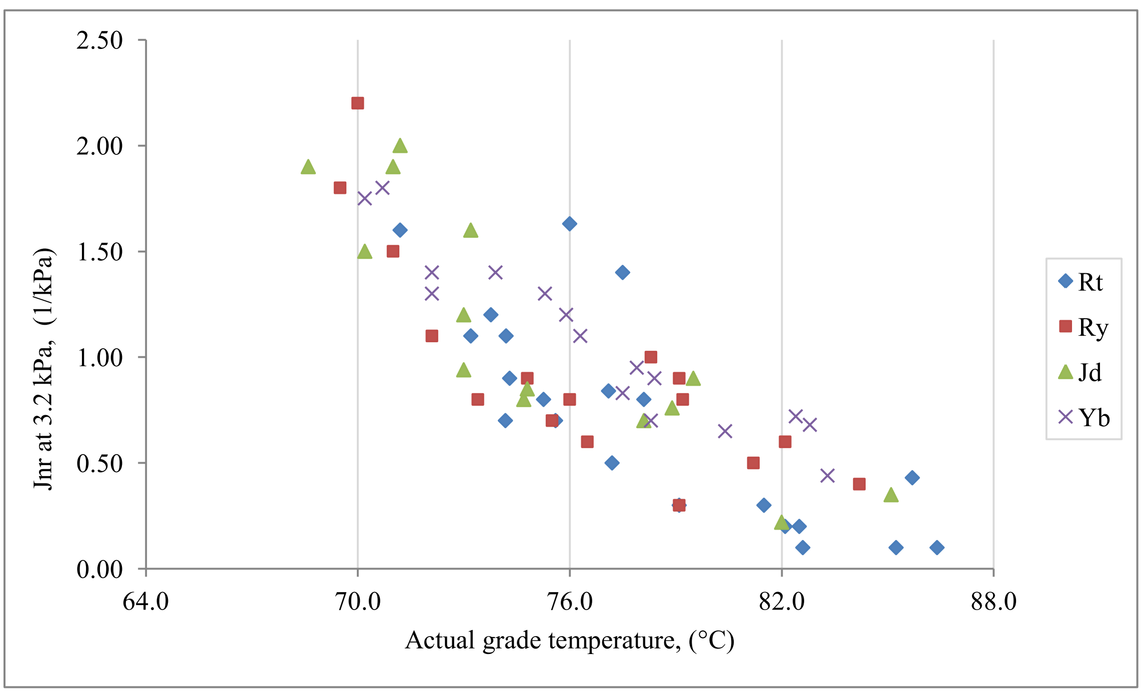


Figure 4. 24. Effect of asphalt source on Jnr values at 3.2 kPa.

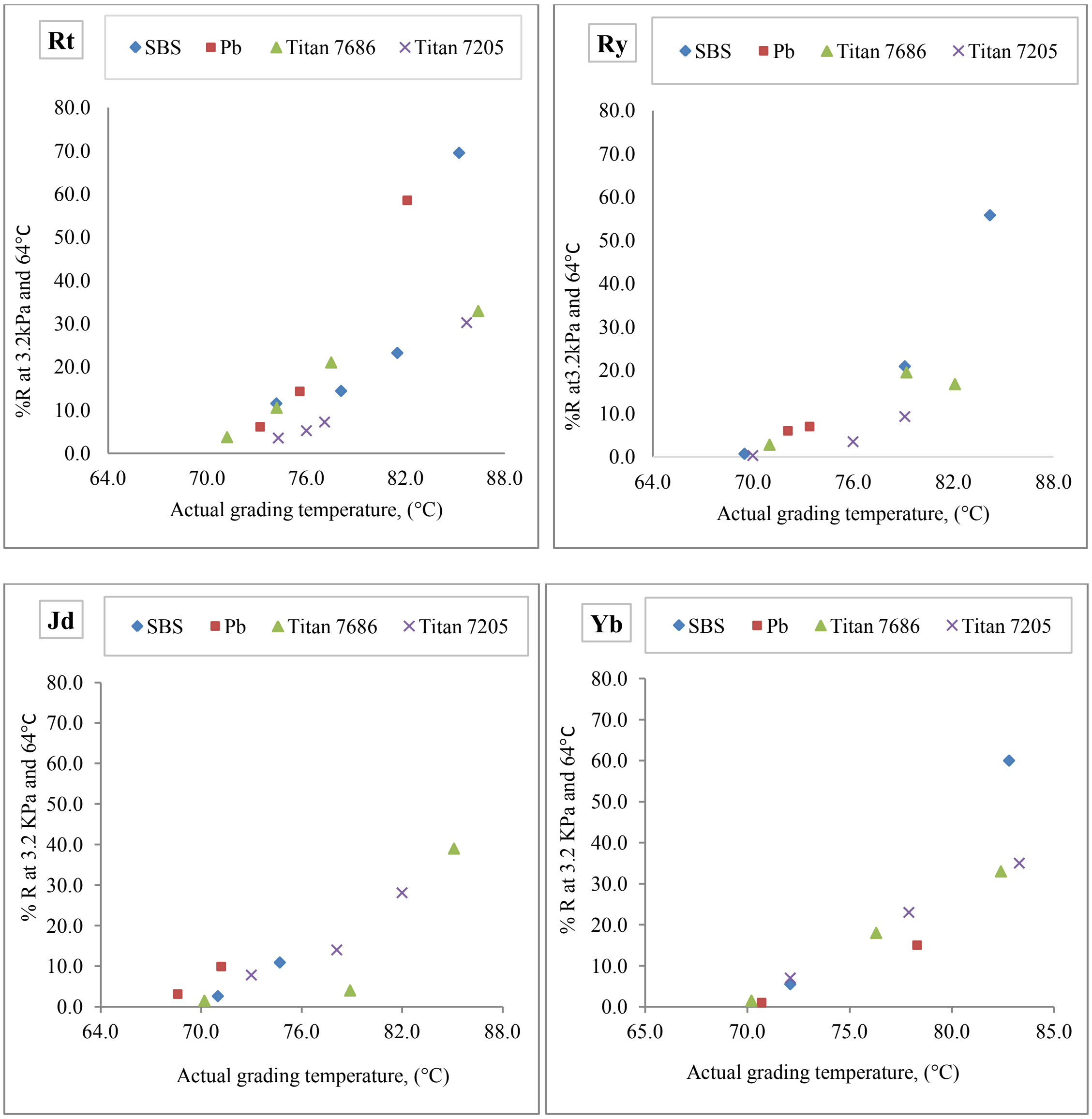


Figure 4. 25. Effect of polymer type and Asphalt source on percent recovery
a) Ras Tannura Asphalts b) Riyadh Asphalts
c) Jeddah Asphalts d) Yanbu Asphalts

Ras Tannura asphalt shows the best performance in resisting rutting when modified with SBS, Polybilt and Titan 7686 polymers and the worst when adding Titan 7205 polymer. Jeddah Asphalt shows the best performance when modified with Titan 7205.

4.4. Correlation between Elastic Recovery and MSCR

One of the main objectives of this research is to study the correlation between percent recovery using ER test and percent recovery using MSCR test in order to evaluate the possibility of replacing the ER with MSCR which is faster, smaller sample size and more fundamental because it is conducted at 64°C not 25°C.

To evaluate this relationship, all the results of different asphalt sources and polymer types were combined together to find out the general relationship between the MSCR and ER. Figure 4.26 shows the relationship between percent recovery values using both tests.

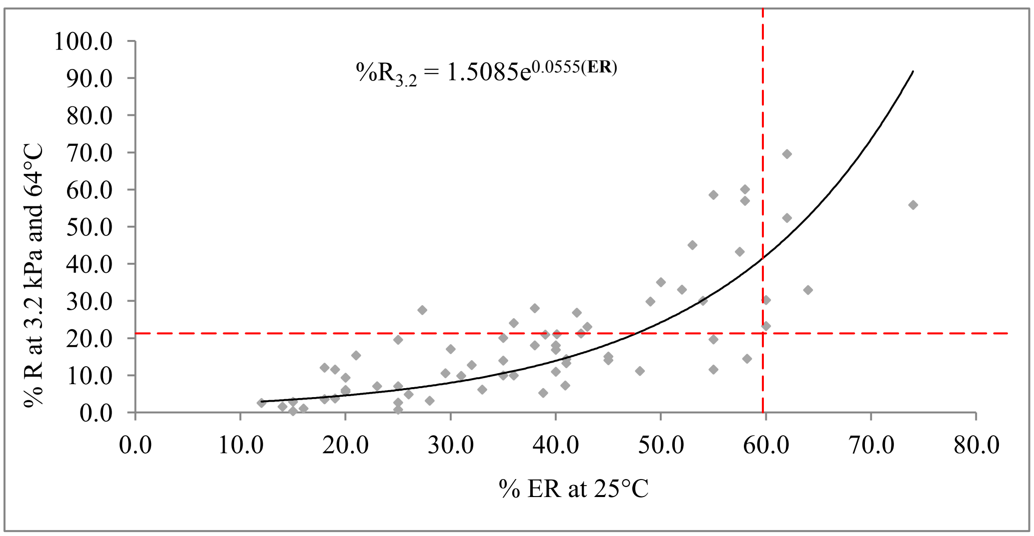


Figure 4. 26. Relationship between Elastic Recovery at 25°C and % $R_{3.2kPa}$ and 64°C.

$$\mathbf{\%R_{3.2}} = 1.51e^{0.06\mathbf{ER}} \tag{4.7}$$

Where $\%R_{3.2}$ is the percent recovery at stress level of 3.2 kPa and testing temperature of 64°C and, ER is the percent elastic recovery using ductility bath test at 25°C.

This equation is used to estimate percent recovery using MSCR test from a given value of conventional ER tests for all the selected asphalt sources and polymer types in this study. It is clear that there is non-linear relationship between the two parameters and coefficient of determination (R^2) of 0.60.

The dashed lines shown in Figure 4.26 represents minimum requirements of each test which specified by the researchers in the literature. These lines divide the plotted area into four divisions. The points in the upper right passed the recovery criteria of both tests. In the other hand, the lower left region represent the rejected results.

For the stress level of 0.1 kPa, there is no specific limit mentioned in previous studies that accept or reject the results when correlate between ER and MSCR. In this study, Figure 4.27 shows that there is a weak relationship between the two tests.

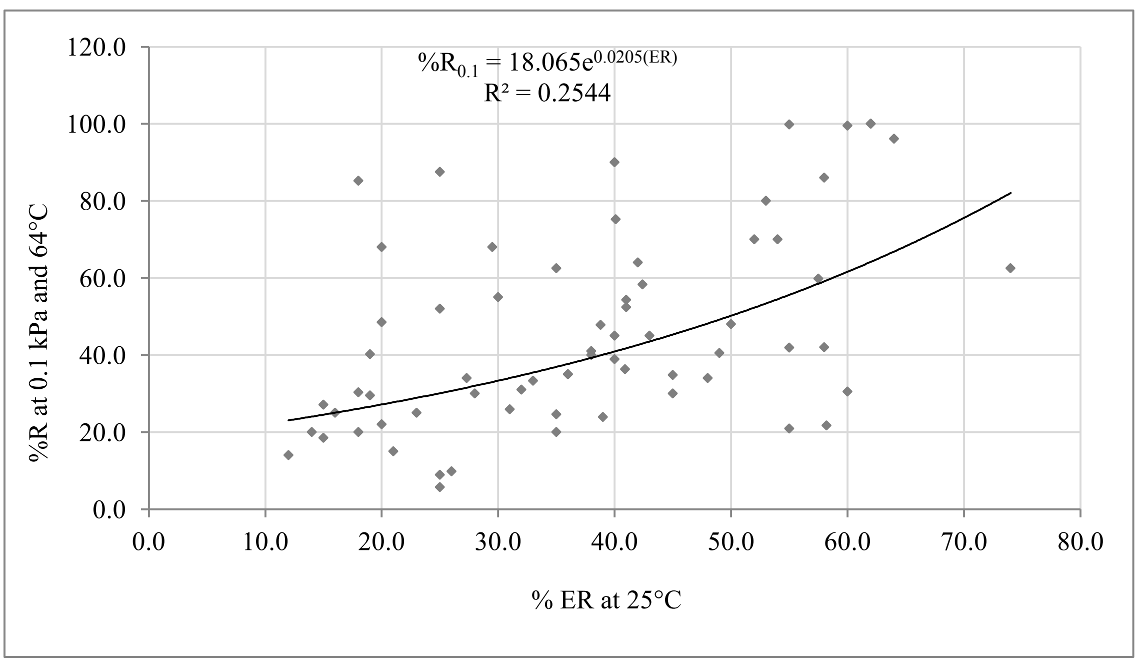


Figure 4. 27. Relationship between Elastic Recovery at 25°C and % $R_{0.1\ kPa}$ at 64°C.

When studying the relationship between Elastic Recovery and multiple stress creep recovery values of asphalt samples which were modified with different types of polymers at low stress level (0.1 kPa), a weak correlation model is obtained with R^2 equals to 0.2544. This leads to a conclusion that the behavioral effect of plastomers and elastomers on asphalt binder at low stress levels is significantly different, while this behavior is similar at higher levels of stress as shown from Figure 4.27.

Polymer modified asphalts have high molecular weight, at low shear rates i.e. 0.1 kPa inter-chain entanglements greatly increase the viscosity and reduce the elasticity, as shear rate increases *i.e.* 3.2 kPa. The individual chains become more oriented along the lines of flow.

To illustrate the difference between plastomeric and elastomeric modification of asphalt binders and the effect of shear rates, it is better to study each of them separately. First step is to study shear rate dependency of elastic polymer on asphalt binder by

4.4.1. Difference between Elastomers and Plastomers

Elastomers such as SBS and plastomers like Polybilt and Titan polymers were studied separately. Figure 4.28 and 4.29 show the relationship between ER and MSCR at different stress levels for the elastomers polymer.

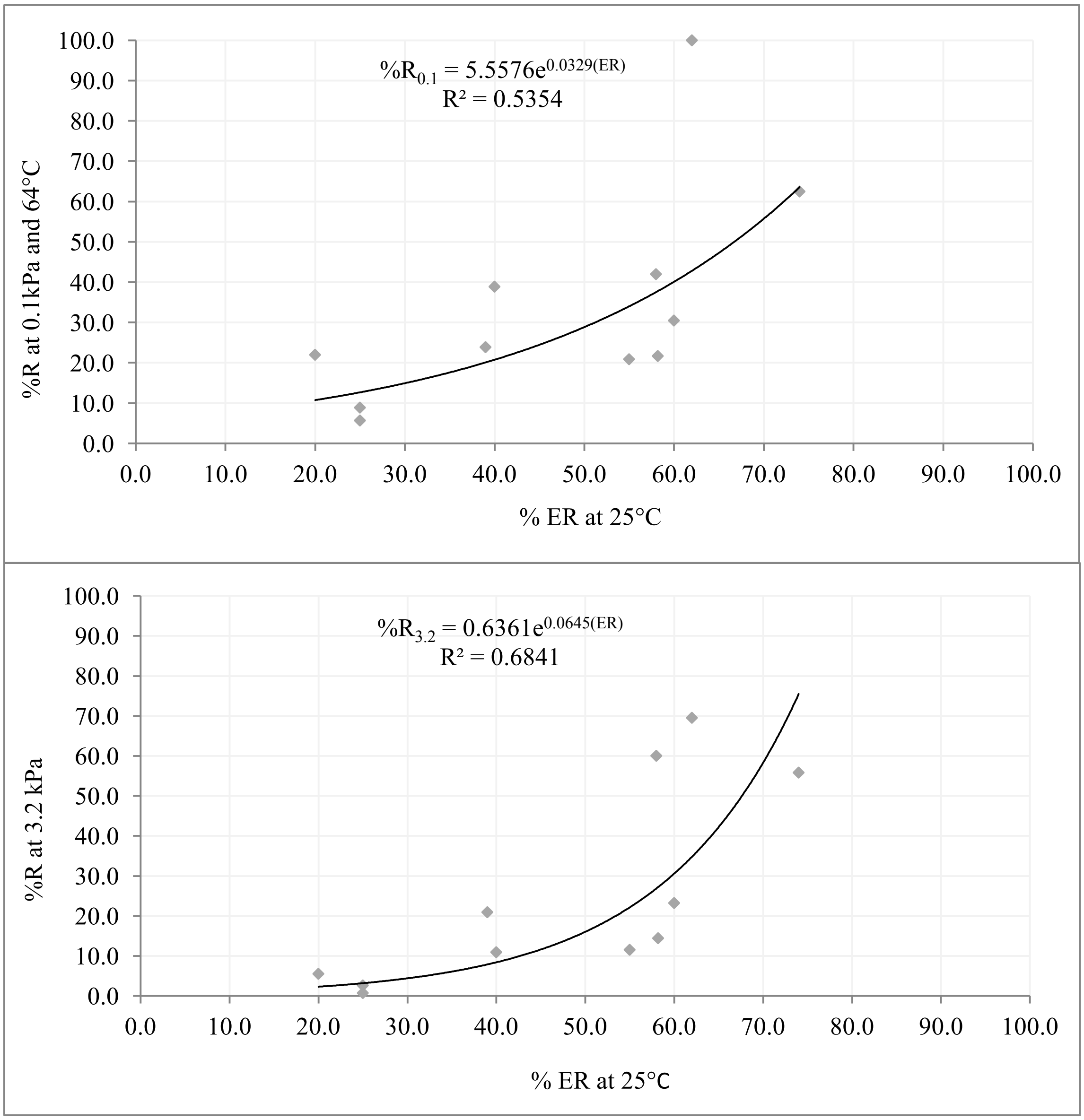


Figure 4. 28. Effect of elastomers on the MSCR-ER relationship at 0.1 kPa

By comparing the models in Figures 4.28 and 4.29 with those shown in Figure 4.26 and 4.27, better relations are shown when studying the polymer groups separately, the value of R^2 is obviously improved from 0.254 to 0.535 at 0.1 kPa stress level and slightly improved for the stress level of 3.2 kPa. Also for the plastomeric polymers, the correlation between the two testing methods has improved as shown in Figure 4.29.

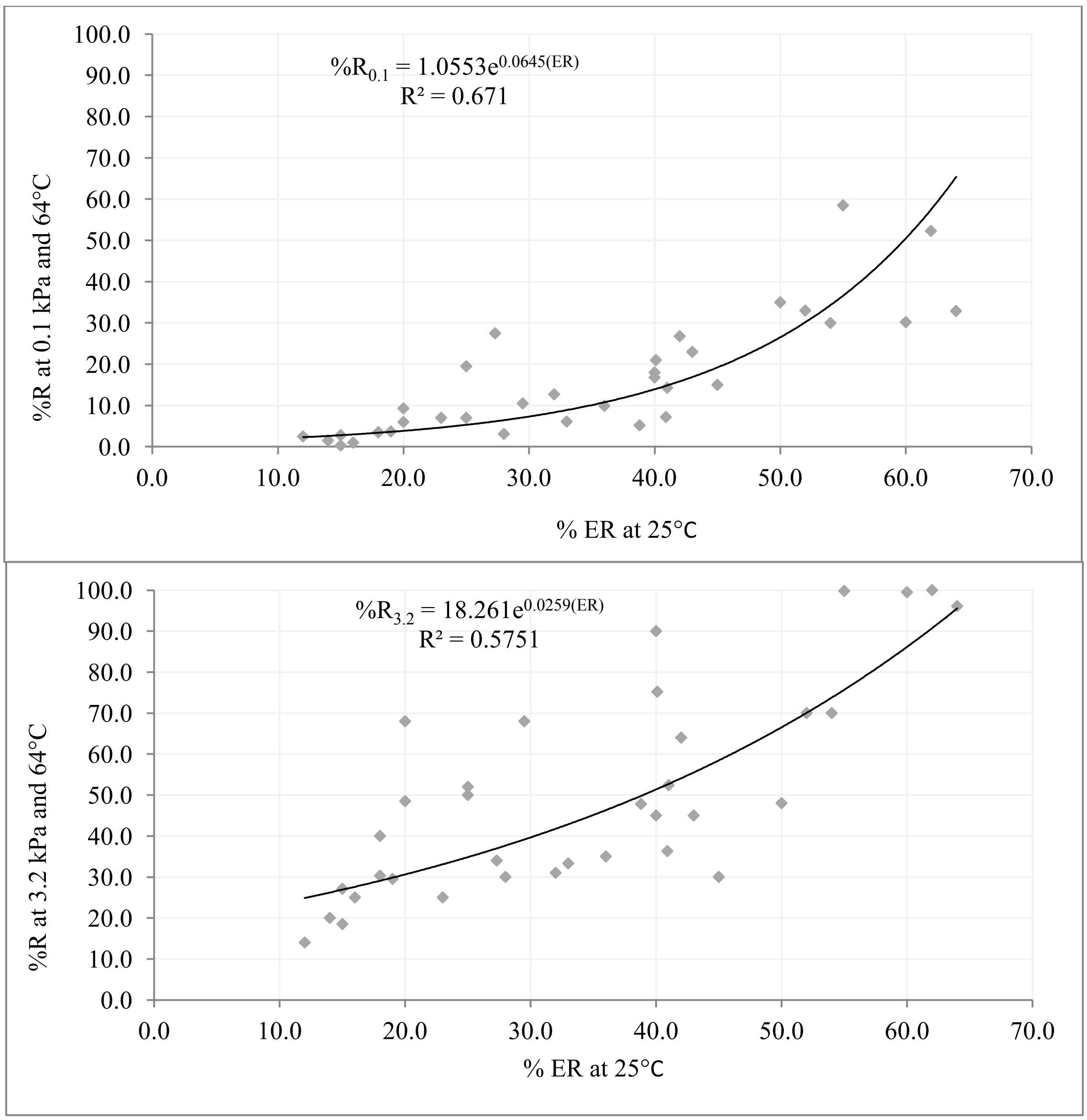


Figure 4. 29. Effect of Plastomers on the MSCR-ER relationship

4.5. Summary of the results

SBS polymer show the best performance in improving the performance grade and elastic recovery behavior of the modified asphalt while other polymers have similar behavior, a general relationship between the PG high performance temperature and the affecting variables that includes; percent polymers (**%P**), polymer type ($\mathbf{P_{type}}$) and source of asphalt (**R**). The important findings of this study can be summarized in Table 4.21 below.

Table 4. 21. Summary of the developed equations from the study.

Polymer	Equation	R^2
SBS	$\mathbf{PG} = 69.49 + 3.412\ (\mathbf{P}_{SBS}) - 2\mathbf{R}$*	0.957
Polybilt 101	$\mathbf{PG} = 66.165 + 2.713\ (\mathbf{P}_{Pb}) - 1.173\mathbf{R}$	0.926
Titan 7686	$\mathbf{PG} = 3.165\ \mathbf{P}_{T6} + 64.224$	0.898
Titan 7205	$\mathbf{PG} = 2.879\ \mathbf{P}_{T5} + 65.94$	0.864
All types	$\mathbf{PG} = 68.11 - 0.974\ (\mathbf{R}) + 4.23\ (\mathbf{\%P}) - 1.498\ (\mathbf{P_{type}})$**	0.678
All Types	$\mathbf{ER} = 2.783\ \mathbf{PG} - 176.08$	0.691
All Types	$\mathbf{\%R_{3.2}} = 1.51e^{0.06.\mathbf{ER}}$	0.600

* This is limited to the four sources studied in this research (Ras Tannura, Riyadh, Jeddah and Yanbu)

** This is limited to the four polymers and their combinations mentioned in the study.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Asphalt binders are playing key role in the performance of flexible pavements when subjected to extreme traffic loads and harsh environment. Hot asphalt mixes should be designed properly to ensure the required behavior at critical conditions. This has led to an increased demand to modify asphalt binders to improve the performance of local asphalt binders to minimize cracking stress, which occurs at low temperatures, and permanent deformation, which occurs at high service-temperatures.

Polymers have remarkable effects on increasing the performance grade of the asphalt binders as shown from this study. The performance grading system is not adequate to evaluate the polymer modified asphalts resistance against rutting and the recovery criterion should be used in the evaluation process.

The main goal of this research study is to evaluate the applicability of elastic and multiple stress creep recovery specifications on Arabian asphalt which is modified with commercial polymers and to recommend minimum requirements of MSCR which can be used by Ministry of Transportation and other asphalt agencies in the region. MSCR requirement is intended to replace the Performance Grading and Elastic Recovery evaluation systems of asphalt binder.

5.1. Conclusions

5.1.1. Asphalt source and variability

The physical and rheological properties of asphalt binders are influenced by its chemical composition and production process. Based on PG, ER and MSCR test results, Ras Tannura asphalt showed the best performance in resisting rutting when modified with SBS, Polybilt and Titan 7686 polymers and the worst when adding Titan 7205 polymer. Jeddah Asphalt gave the best performance when modified with Titan 7205.

5.1.2. Polymer effect on Arabian asphalt

Four polymers were used to improve asphalts. Polymer additive should be sufficiently compatible with the asphalt to avoid phase separation during the storage and transportation.

SBS polymer showed a remarkable behavior in improving rutting resistance. Adding 1.6% of the polymer (% of binder weight) is sufficient to meet PG 70. Adding 3.3% and 5.1% will improve the PG to become PG 76 and PG 82, respectively. Polybilt 101 performs the worst among the polymers, where adding 2.5%, 4.7% and 6.9% is needed to meet PG 70, PG 76 and PG 82, respectively.

On average, 1.8% of polymer would improve the Arabian Asphalt to meet PG 70, 3.8% for PG 76 and 5.8% for PG 82.

5.1.3. Elastic Recovery

The results of Elastic Recovery (AASHTO T 51) test show that there is linear relationship between the actual grade temperature and percent recovery at 25°C. Even though, this test is empirical and takes more than 4 hours to test one sample, the test is still accepted by many asphalt agencies and used as a rule of thumb.

Arabian asphalts that have PG 70 can recover about 20% as percent recovery, and about 30% of PG 76. While asphalt samples of PG 82 has about 50% recovery.

5.1.4. Multiple Stress Creep Recovery (MSCR)

An exponential relationship was found between temperature and percent recoverable strain using MSCR requirements with good correlation. MSCR test can be used as a replacement of the conventional Elastic Recovery test; it is more scientific, realistic and saves time and cost of testing.

The analysis of MSCR test indicates that for the Arabian asphalts; there are good relationship between actual grade temperature and percent recoverable strain after 9 seconds and using 3.2 kPa stress level for creep and for 1 second, the same results are shown for the non-recoverable compliance Jnr. While at stress level of 0.1 kPa the correlation is less than the 3.2 kPa. That can be explained by different behavior of plastomer, like Polybilt and Titans, and elastomers like SBS.

5.1.5. Suggested limit of MSCR for polymer modified Arabian asphalts

Results indicated that the conventional Elastic Recovery test can be replaced by the MSCR test which saves time and cost of testing. From the results of correlation between the two tests, it is shown that %40 of percent recovery using MSCR test at 3.2 kPa and 64°C testing temperature is equivalent to 60% when testing the same sample combination using the Elastic Recovery test at 25°C.

This important result can be used as a limit when designing the asphalt binder for rutting resistance of Arabian Asphalt.

5.2. Recommendations for future study

- To study the effect of polymer modifications in improving rutting resistance by correlating the Jnr to rut depth of field road sections.

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APPENDICES

APPENDIX A

Superpave performance grading system

Table A. 1. G*/sin (δ) values of Ras Tannura asphalts modified with Titan 7686.

Ras Tannura Asphalt		100%	98%	97%	96%	95%	94%
Honeywell Titan™ 7686		0%	2%	3%	4%	5%	6%
Total		**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Original Binder	Temp (°C)						
G*/sin(δ) (> 1.0 kPa)	64	1.09	3.304	5.155	4.251	5.963	8.119
G*/sin(δ) (> 1.0 kPa)	70	0.7533	1.805	3.055	2.183	3.286	4.789
G*/sin(δ) (> 1.0 kPa)	76	0.432	1.026	1.744	1.212	1.826	3.008
G*/sin(δ) (> 1.0 kPa)	82	0.298	0.6307	1.138	0.7295	1.032	1.884
Pass/Fail Temp.		**66**	**75.9**	**76.2**	**78**	**82**	**88**
RTFO RESIDUE	Temp (°C)						
G*/sin(δ) (>2.2 kPa)	64	2.399	5.135	5.939	7.285	7.877	12.25
G*/sin(δ) (>2.2 kPa)	70	1.811	2.546	3.104	3.814	3.977	6.304
G*/sin(δ) (>2.2 kPa)	76	0.923	1.532	1.781	2.003	2.046	3.448
G*/sin(δ) (>2.2 kPa)	82	0.198	0.891	0.987	1.08	1.46	1.845
Pass/Fail Temp.		**66**	**71**	**73**	**75**	**75**	**80**
Actual PG Grade		66	71	73	75	75	80

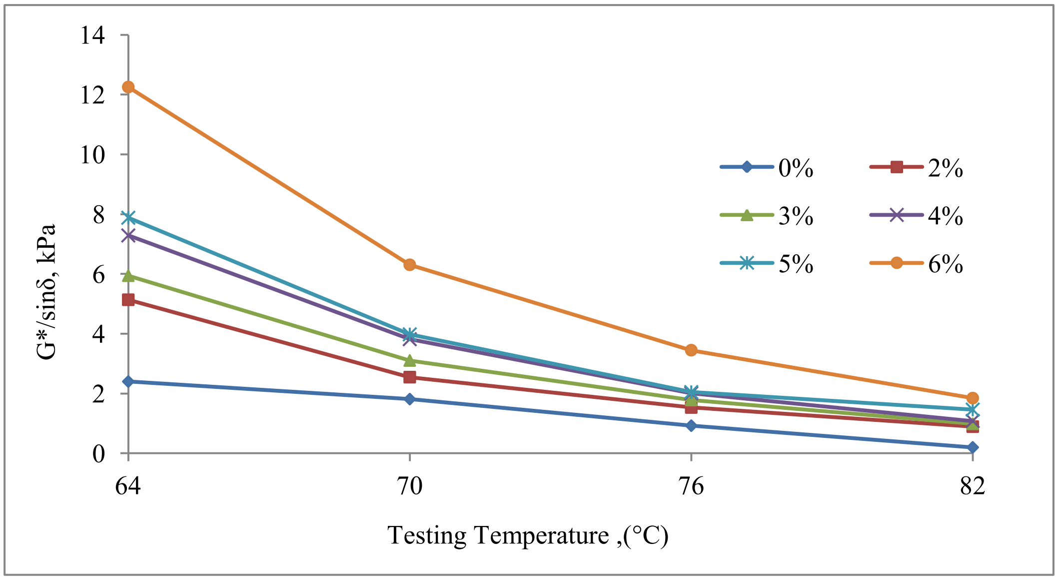

Figure A. 1. Ras Tannura Asphalt modified with Titan7686 at fresh conditions.

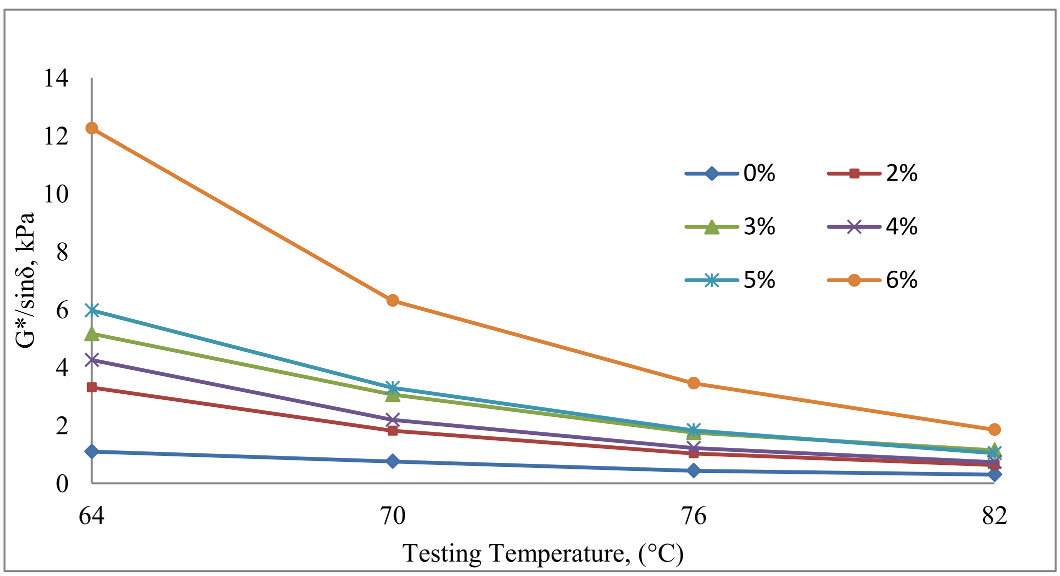

Figure A. 2. Ras Tannura Asphalt modified with Titan 7686 at short-term ageing conditions.

Table A. 2. G*/sin (δ) values of Ras Tannura asphalts modified with Titan 7205

Ras Tannura Asphalt		100%	98%	97%	96%	95%	94%
Honeywell Titan™ 7205		0	2%	3%	4%	5%	6%
Total		**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Original Binder	Temp (°C)						
G*/sin(δ) (> 1.0 kPa)	64	1.09	3.527	3.963	4.69	6.076	7.425
G*/sin(δ) (> 1.0 kPa)	70	0.7533	2.086	2.569	2.929	3.593	4.332
G*/sin(δ) (> 1.0 kPa)	76	0.432	1.386	1.721	1.816	2.172	2.77
G*/sin(δ) (> 1.0 kPa)	82	0.298	1.009	1.219	1.246	1.321	1.754
Pass/Fail Temp.		**66**	**78**	**83**	**84**	**85**	**86**
RTFO RESIDUE	Temp (°C)						
G*/sin(δ) (>2.2 kPa)	64	2.399	5.865	6.978	8.706	8.973	11.68
G*/sin(δ) (>2.2 kPa)	70	1.811	3.248	3.977	4.518	5.247	6.508
G*/sin(δ) (>2.2 kPa)	76	0.923	1.532	2.143	2.88	3.048	3.632
G*/sin(δ) (>2.2 kPa)	82	0.198	0.698	1.021	1.532	1.76	2.04
Pass/Fail Temp.		**66**	**74**	**76**	**77**	**80**	**81**
Actual PG Grade		66	74	76	77	80	81

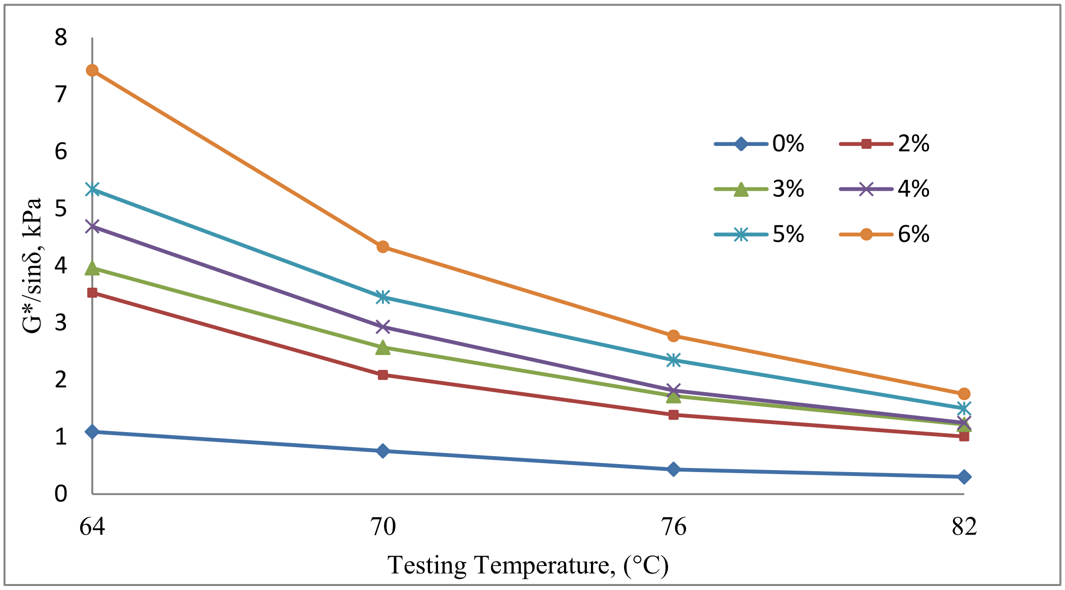

Figure A. 4. Ras Tannura Asphalt modified with Titan 7205 at short-term ageing conditions.

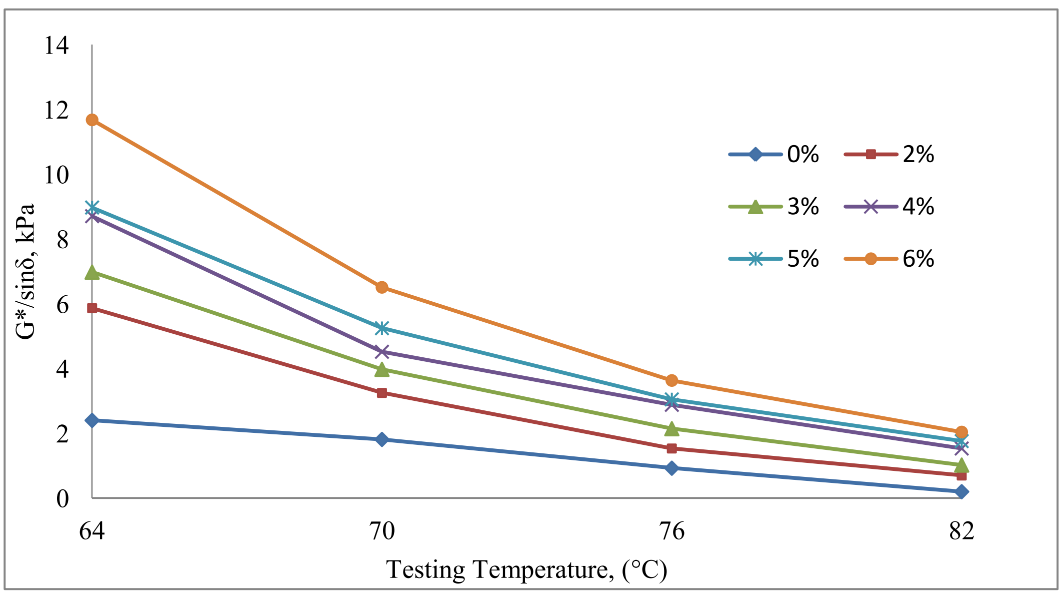

Figure A. 3. Ras Tannura Asphalt modified with Titan 7205 at short-term ageing conditions.

Table A. 3. G*/sin (δ) values of Ras Tannura asphalts modified with Titan SBS

Ras Tannura Asphalt		100.00%	98.00%	97.00%	96.00%	95.00%	94.00%
SBS		0.00%	2.00%	3.00%	4.00%	5.00%	6.00%
Total		**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Original Binder	**Temp (°C)**						
G*/sin(δ) (> 1.0 kPa)	64	1.09	3.174	5.044	4.233	6.123	5.341
G*/sin(δ) (> 1.0 kPa)	70	0.7533	1.713	3.067	2.812	3.641	3.451
G*/sin(δ) (> 1.0 kPa)	76	0.432	1.018	1.87	1.798	2.239	2.347
G*/sin(δ) (> 1.0 kPa)	82	0.298	0.7384	1.106	1.101	1.343	1.498
Pass/Fail Temp.		**66**	**76.20**	**83.60**	**84.20**	**85.60**	**88.50**
RTFO RESIDUE	**Temp (°C)**						
G*/sin(δ) (>2.2 kPa)	64	2.399	9.324	10.12	10.98	12.12	13.432
G*/sin(δ) (>2.2 kPa)	70	1.811	6.204	7.890	8.967	9.296	10.432
G*/sin(δ) (>2.2 kPa)	76	0.923	2.996	4.112	5.321	6.542	7.221
G*/sin(δ) (>2.2 kPa)	82	0.198	1.410	2.098	3.21	4.879	5.12
Pass/Fail Temp.		**66**	**74.2**	**78.1**	**81.5**	**85.2**	**89.3**
Actual PG Grade		66	**74.2**	**78.1**	**81.5**	**85.2**	**89.3**

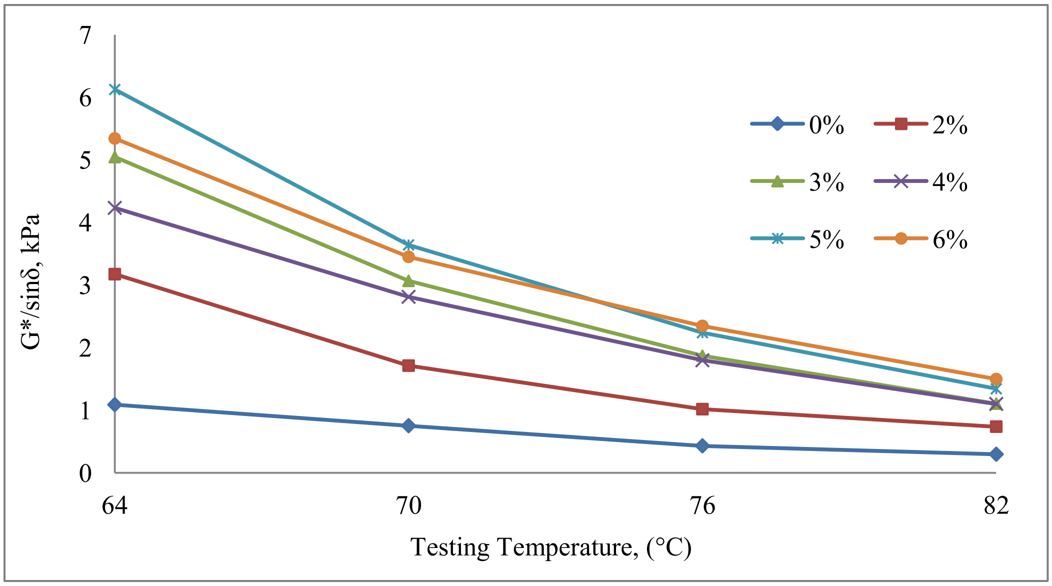

Figure A. 5. Ras Tannura Asphalt modified with Titan SBS at short-term ageing conditions.

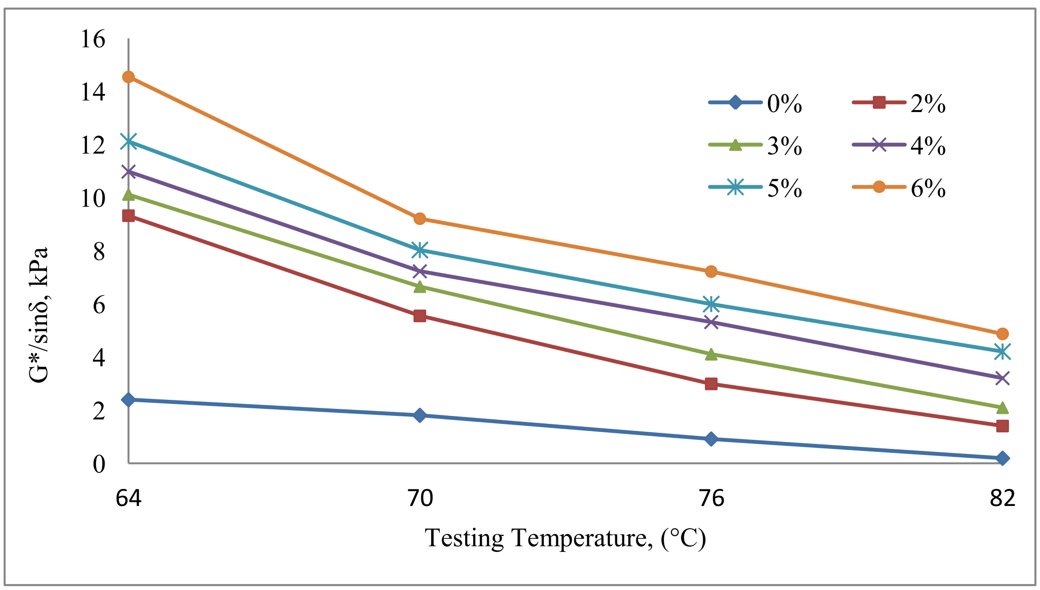

Figure A. 6. Ras Tannura Asphalt modified with Titan SBS at short-term ageing conditions.

Table A. 4. G*/sin (δ) values of Ras Tannura asphalts modified with Titan Polybilt 101

Ras Tannura Asphalt		100.00%	98.00%	97.00%	96.00%	95.00%	94.00%
Polybilt 101		0.00%	2.00%	3.00%	4.00%	5.00%	4.00%
Total		1.0	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Original Binder	**Temp (°C)**						
G*/sin(δ) (> 1.0 kPa)	64	1.09	2.4	3.2	4.3	5.78	6.98
G*/sin(δ) (> 1.0 kPa)	70	0.7533	1.5	2.0	2.540	3.20	4.01
G*/sin(δ) (> 1.0 kPa)	76	0.432	0.8	1.100	1.760	2.2	2.95
G*/sin(δ) (> 1.0 kPa)	82	0.298	0.65	0.780	1.120	1.87	2.03
Pass/Fail Temp.		**66.0**	**75.2**	**78.8**	**80.6**	**81.8**	**86**
RTFO RESIDUE	**Temp (°C)**						
G*/sin(δ) (>2.2 kPa)	64	2.399	5.33	6.87	8.11	9.87	11.22
G*/sin(δ) (>2.2 kPa)	70	1.811	3.12	3.980	4.553	6.00	6.98
G*/sin(δ) (>2.2 kPa)	76	0.923	1.54	1.900	2.083	2.99	3.87
G*/sin(δ) (>2.2 kPa)	82	0.198	1.03	1.300	1.550	2.01	2.56
Pass/Fail Temp.		**66**	70.9	73.2	**75.6**	78.9	**82.1**
Actual PG Grade		**66.0**	**70.9**	**73.2**	**75.6**	**78.9**	**82.1**

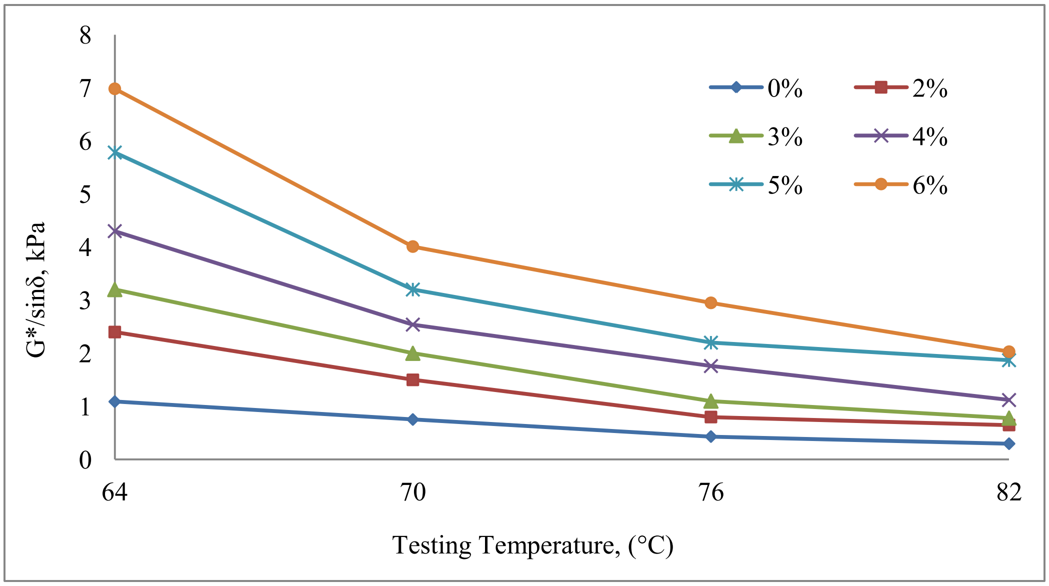

Figure A. 7. Ras Tannura Asphalt modified with Polybilt 101 at short-term ageing conditions.

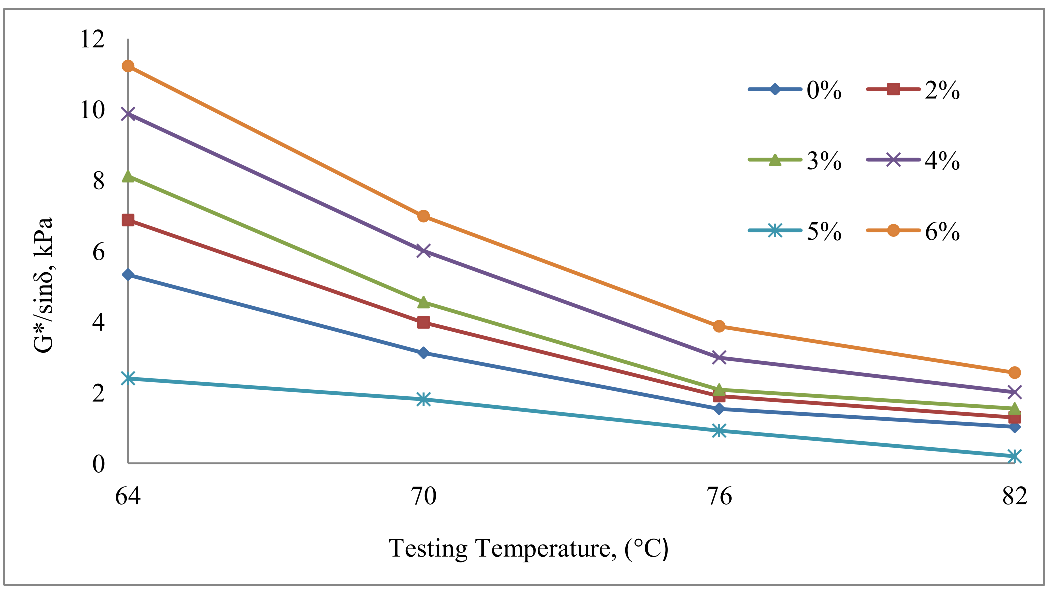

Figure A. 8. Ras Tannura Asphalt modified with Polybilt 101 at short-term ageing conditions.

APPENDIX B

Elastic Recovery Test Results

Table B. 1. Percent Recovery values for Riyadh Asphalts with different polymers.

Additive Name	Actual Upper pass. Temp.	True PG	DB % Recovery at 25°C
None	64.2	PG 64	0.0
SBS	69.5	PG 70	25.0
	79.1	PG 76	39.0
	84.2	PG 82	74.0
Pb 101	72.1	PG 70	20.0
	73.4	PG 70	25.0
Titan 7686	71.0	PG 70	15.0
	79.2	PG 76	25.0
	82.1	PG 82	40.0
Titan 7205	70.0	PG 70	15.0
	76.0	PG 76	18.0
	79.1	PG 76	20.0
SBS: Titan 7686	75.5	PG 76	38.0
	76.5	PG 76	45.0
SBS:Titan 7205	74.8	PG 70	26.0
	78.3	PG 76	48.0
	81.2	PG 76	55.0

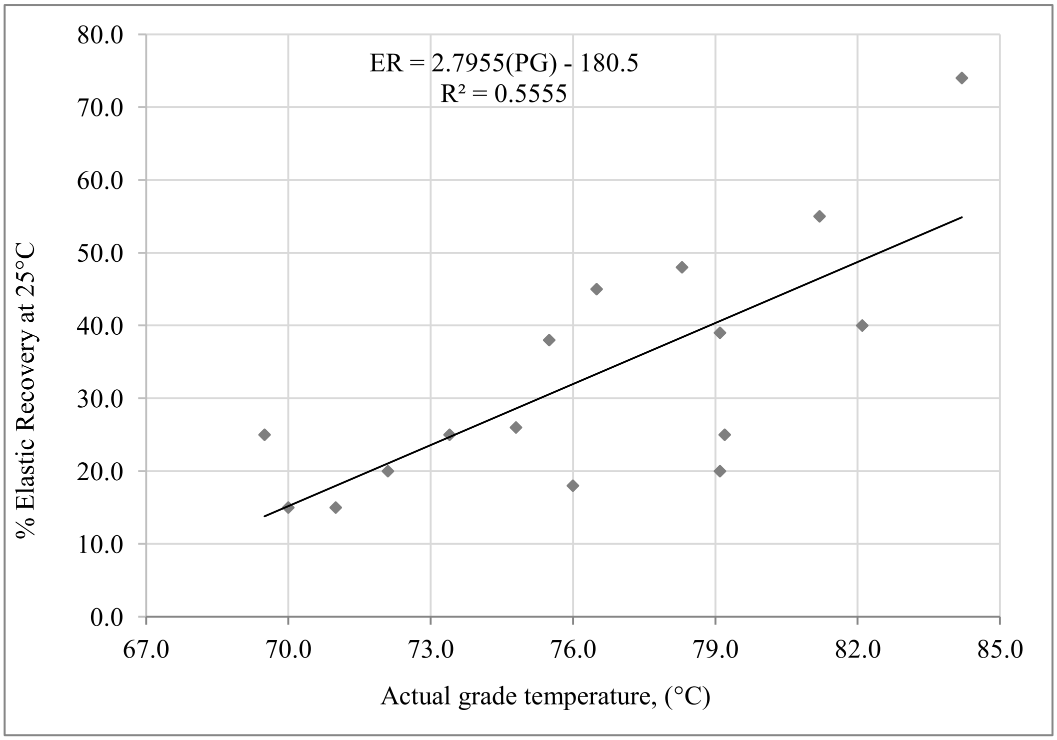

Figure B. 1. Relation between passing temperature and Elastic Recovery for Riyadh Asphalts.

$$\mathbf{ER_{Ry}} = 2.8\ \mathbf{PG} - 180.5$$

Where

$\mathbf{ER_{Ry}}$ is the Elastic Recovery in % for Riyadh Asphalts

PG is the actual grade temperature of the performance grade of the samples

Table B. 2. Percent Recovery values for Jeddah Asphalts with different polymers.

Additive Name	Actual Upper PG Temp. (C°)	True PG	DB % Recovery at 25°C
None	63.3	PG 58	0.0
SBS	71.0	PG 70	25.0
	74.7	PG 70	40.0
Pb 101	68.6	PG 64	28.0
	71.2	PG 70	36.0
Titan 7686	70.2	PG 70	12.0
	78.9	PG 76	27.0
	85.1	PG 82	62.0
Titan 7205	73.0	PG 70	32.0
	78.1	PG 76	42.0
	82.0	PG 82	54.0
SBS: Titan 7686	73.0	PG 70	19.0
	74.8	PG 70	41.0
SBS:Titan 7205	73.2	PG 70	21.0
	79.5	PG 76	35.0

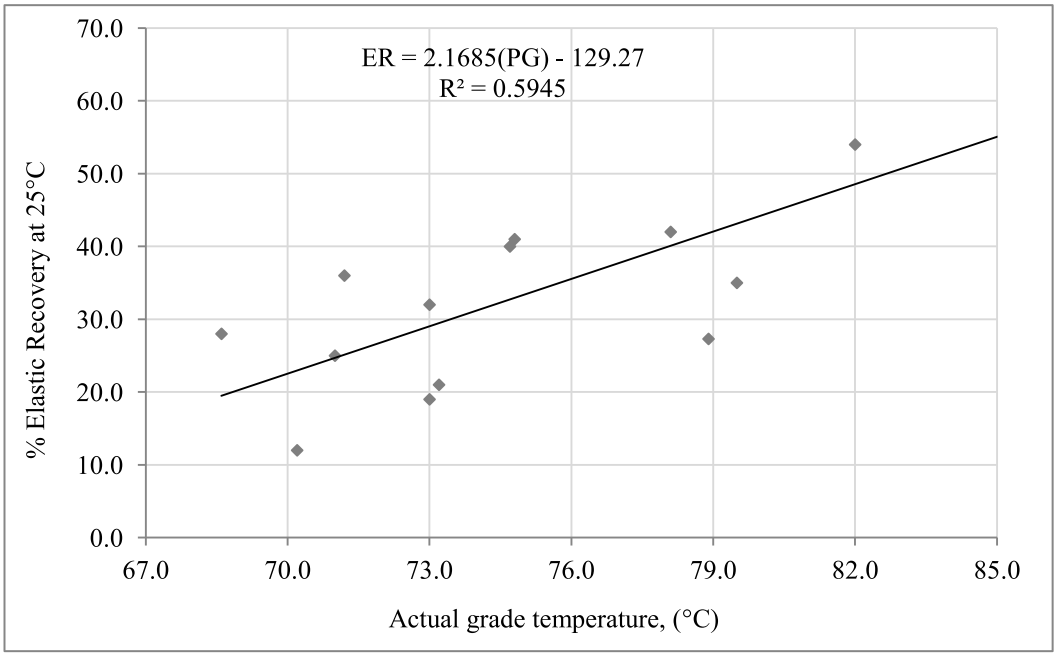

Figure B. 2. Relation between passing temperature and Elastic Recovery for Jeddah Asphalts.

$\mathbf{ER_{Jd}}$ = 2.2 **PG** – 129.3.5

Where:

$\mathbf{ER_{Jd}}$ is the Elastic Recovery in % for Jeddah Asphalts

PG is the actual grade temperature of the performance grade of the samples

Table B. 3. Percent Recovery values for Yanbu Asphalts with different polymers.

Additive Name	**Actual Upper pass. Temp.**	**True PG**	**DB % Recovery at 25°C**
None	63.2	PG 58	0.0
SBS	72.1	PG 70	20.0
	82.8	PG 82	58.0
Pb 101	70.7	PG 70	16.0
	78.3	PG 76	45.0
Titan 7686	70.2	PG 70	14.0
	76.3	PG 76	40.0
	82.4	PG 82	52.0
Titan 7205	72.1	PG 70	23.0
	77.9	PG 76	43.0
	83.3	PG 82	50.0
SBS: Titan 7686	75.3	PG 70	35.0
	75.9	PG 76	36.0
	77.5	PG 76	38.0
SBS:Titan 7205	73.9	PG 70	18.0
	78.4	PG 76	30.0
	80.4	PG 76	53.0

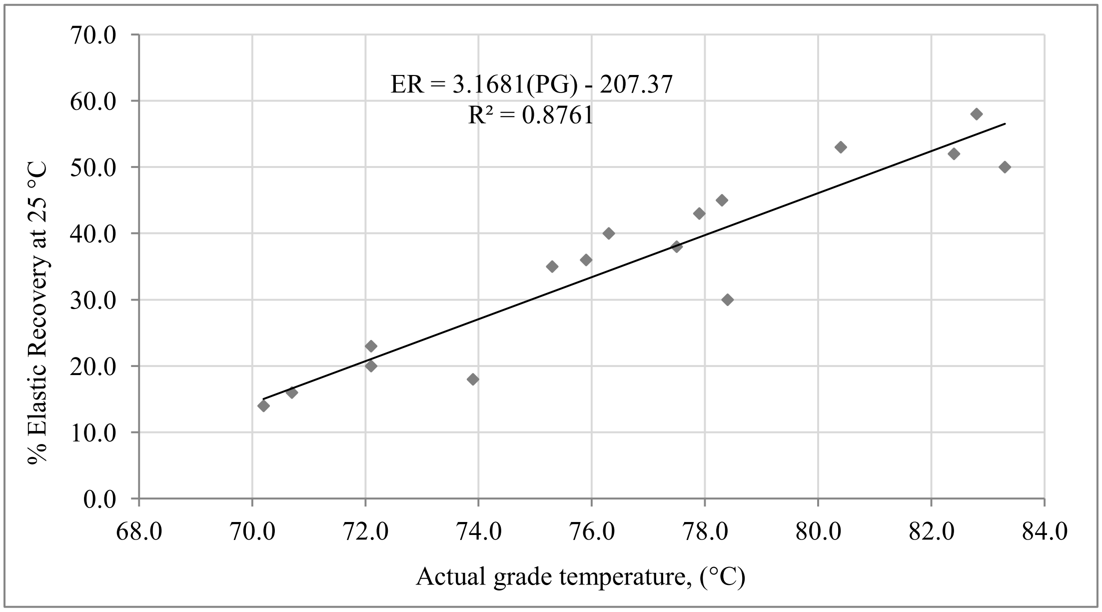

Figure B. 3. Relation between passing temperature and Elastic Recovery for Yanbu Asphalts.

$\mathbf{ER_{Yb}} = 3.2\ \mathbf{PG} - 207.4$

Where

$\mathbf{ER_{yb}}$ is the Elastic Recovery in % for Yanbu Asphalts

PG is the actual grade temperature of the performance grade of the samples

APPENDIX C

MSCR Test Results

Table C. 1. MSCR results for Riyadh modified asphalts.

Additive Name	Actual Upper pass. Temp.	True PG	MSCR at 64°C			
			100 Pa		3200 Pa	
			% $R_{0.1}$	Jnr $_{0.1}$ (Kpa^{-1})	% $R_{3.2}$	Jnr $_{3.2}$ (Kpa^{-1})
None	66.0	PG 64	0.0	0.00	0.0	0.0
SBS	74.2	PG 70	20.9	0.56	11.5	0.70
	78.1	PG 76	21.7	0.67	14.4	0.8
	81.5	PG 76	30.5	0.27	23.2	0.3
	85.2	PG 82	100.0	0.00	69.5	0.1
Polybilt 101	73.2	PG 70	33.3	0.64	6.1	1.1
	75.6	PG 76	52.4	0.35	14.3	0.70
	82.1	PG 82	99.8	0.001	58.5	0.2
Titan 7686	71.2	PG 70	29.5	0.877	3.7	1.60
	74.2	PG 70	68.0	0.206	10.5	1.10
	77.5	PG 76	75.2	0.176	21.0	1.40
	86.4	PG 82	96.1	0.003	32.9	0.10
Titan 7205	74.3	PG 70	30.3	0.50	3.5	0.9
	76.0	PG 76	47.8	0.58	5.2	1.6
	77.1	PG 76	36.3	0.45	7.2	0.84
	85.7	PG 82	99.5	0.001	30.2	0.43
SBS: Titan 7686	73.8	PG 70	24.6	0.85	9.9	1.2
	77.2	PG 76	58.3	0.21	21.2	0.5
	82.5	PG 82	59.8	0.14	43.2	0.2
SBS:Titan 7205	75.3	PG 70	25.9	0.56	9.8	0.8
	79.1	PG 76	40.5	0.26	29.8	0.3
	82.6	PG 82	86.0	0.03	56.9	0.1

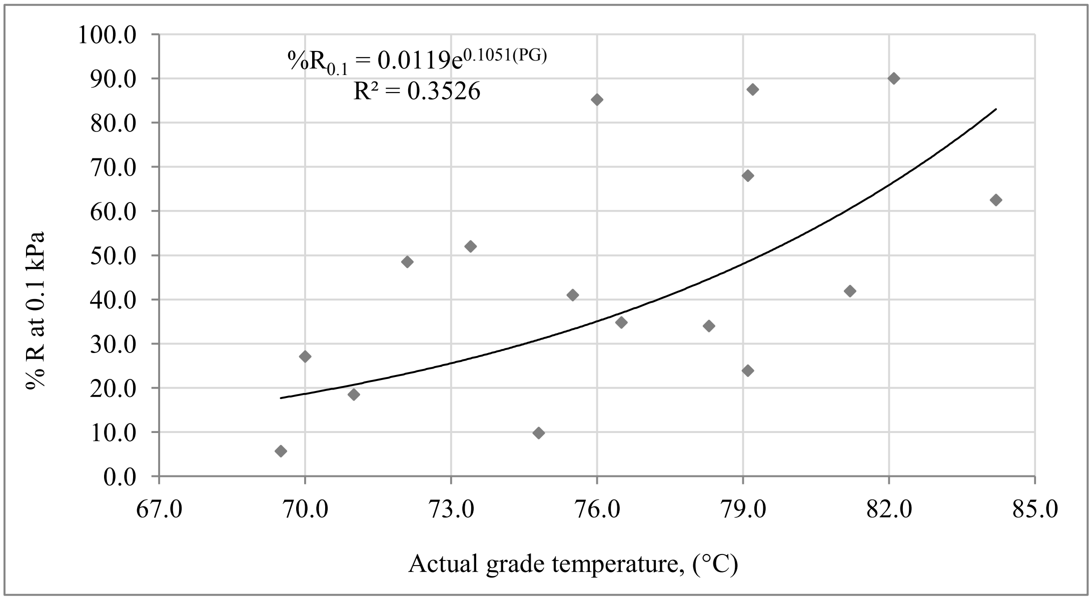

Figure C. 1. Percent recovery at 0.1 kPa per each passing temperature for Riyadh asphalts.

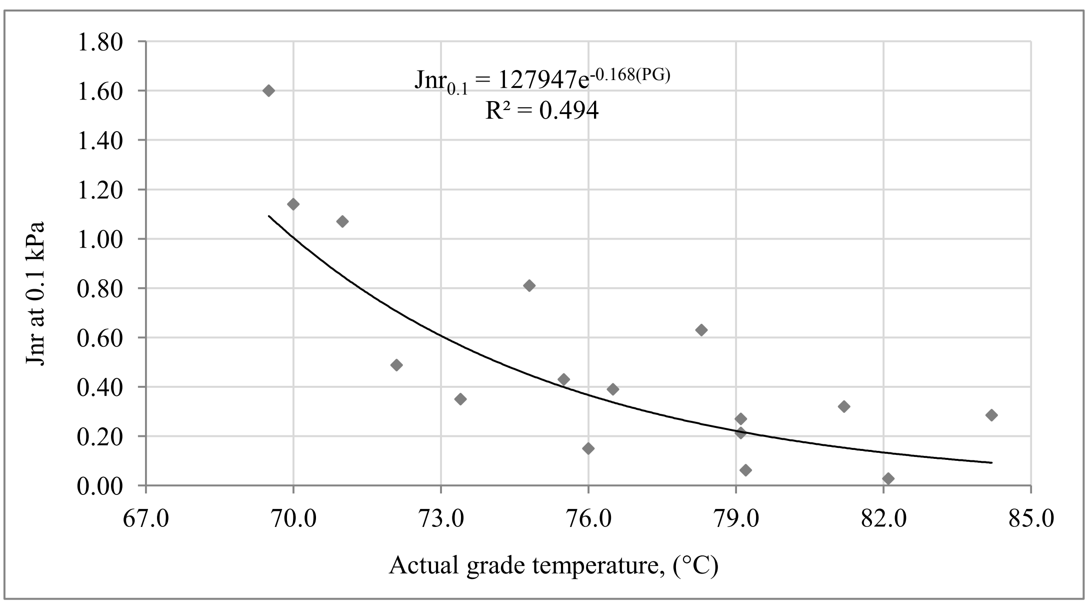

Figure C. 2. Percent recovery at 0.1 kPa per each passing temperature for Riyadh asphalts.

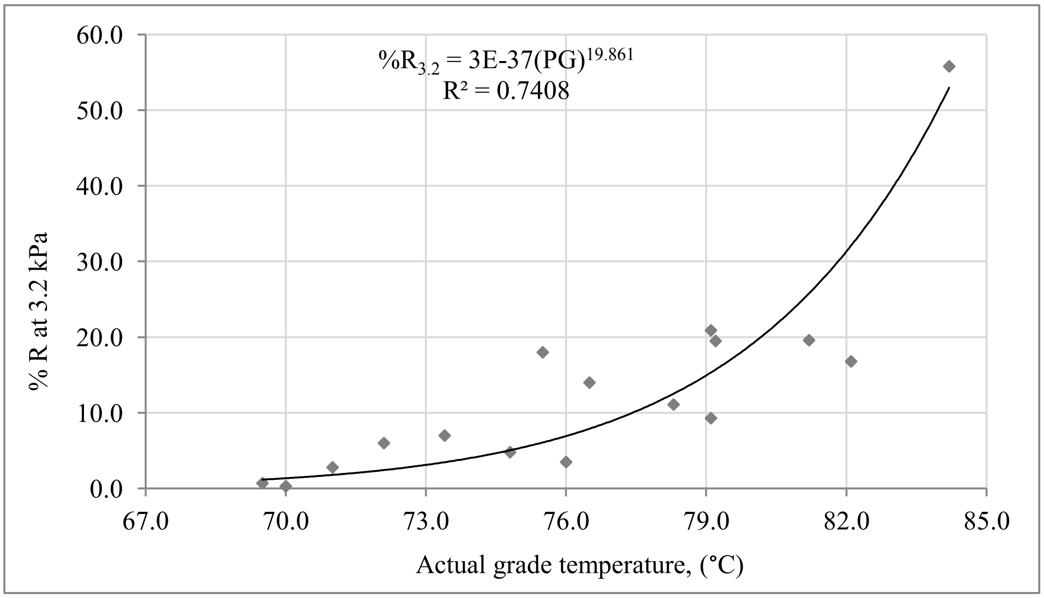

Figure C. 3. Percent recovery at 3.2 kPa per each passing temperature for Riyadh asphalts.

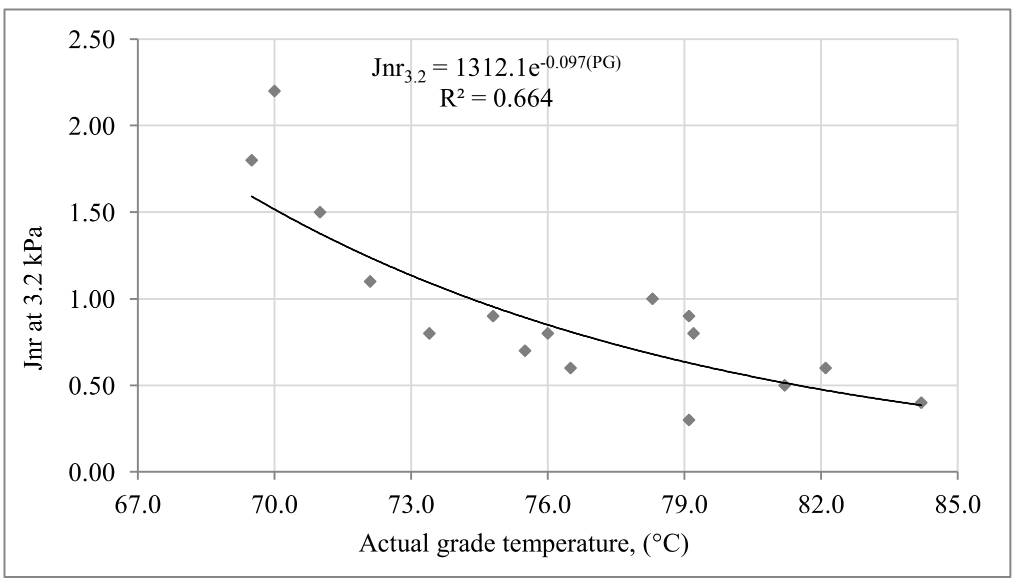

Figure C. 4. Percent recovery at 3.2 kPa per each passing temperature for Riyadh asphalts.

Table C. 2. MSCR results for Jeddah modified asphalts.

Additive Name	**Actual Upper pass. Temp.**	**True PG**	**MSCR at 64°C**			
			100 Pa		**3200 Pa**	
			% $R_{0.1}$	**Jnr $_{0.1}$ (Kpa^{-1})**	**% $R_{3.2}$**	**Jnr $_{3.2}$ (Kpa^{-1})**
None	63.3	PG 58	0.0	0.00	0.0	0.0
SBS	71.0	PG 70	8.9	1.40	2.6	1.90
	74.7	PG 70	38.9	0.48	10.9	0.8
Pb 101	68.6	PG 64	30.0	0.49	3.1	1.9
	71.2	PG 70	35.0	0.44	9.9	2.00
Titan 7686	70.2	PG 70	14.0	1.450	1.5	1.50
	78.9	PG 76	34.0	0.400	4.0	0.76
	85.1	PG 82	100.0	0.00	39.0	0.35
Titan 7205	73.0	PG 70	31.0	0.80	7.8	1.2
	78.1	PG 76	64.0	0.30	14.0	0.7
	82.0	PG 82	70.0	0.10	28.1	0.22
SBS: Titan 7686	73.0	PG 70	40.2	0.50	11.5	0.94
	74.8	PG 70	54.3	0.37	13.2	0.85
SBS:Titan 7205	73.2	PG 70	15.0	0.80	5.9	1.6
	79.5	PG 76	62.5	0.26	13.9	0.9

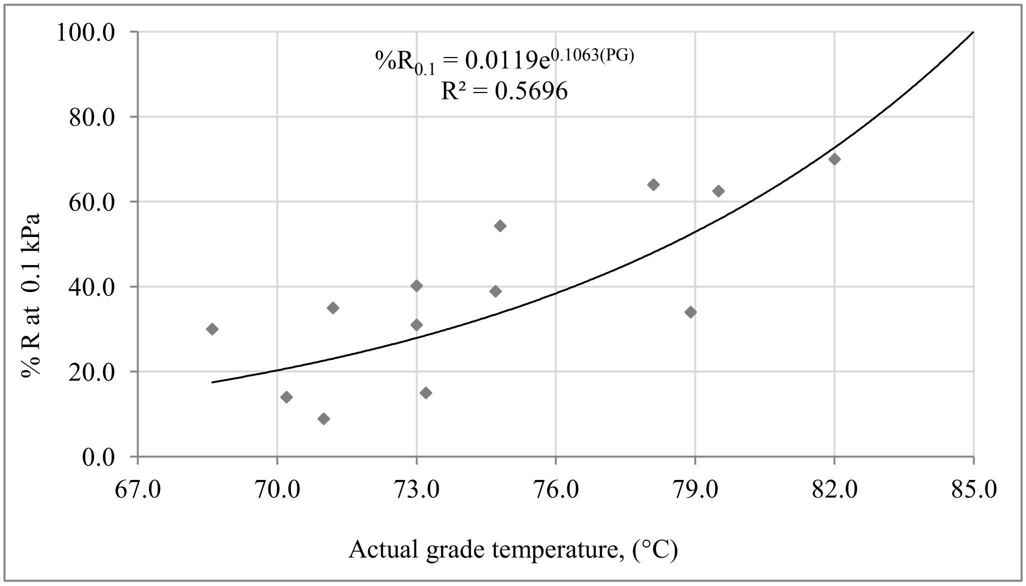

Figure C. 5. Percent recovery at 0.1 kPa per each passing temperature for Jeddah asphalts.

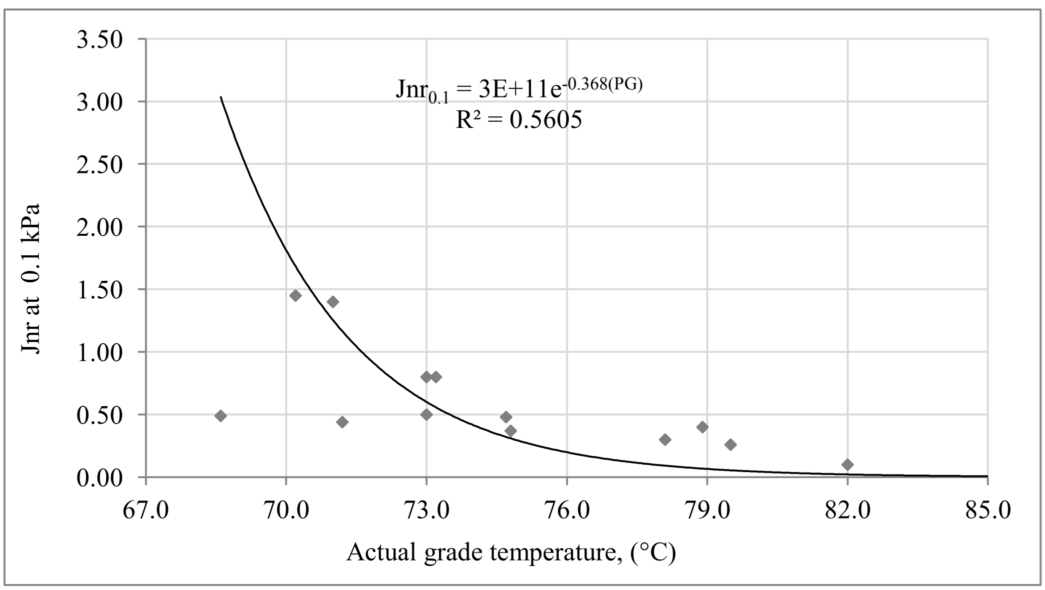

Figure C. 6. Jnr at 0.1 kPa per each passing temperature for Jeddah asphalts.

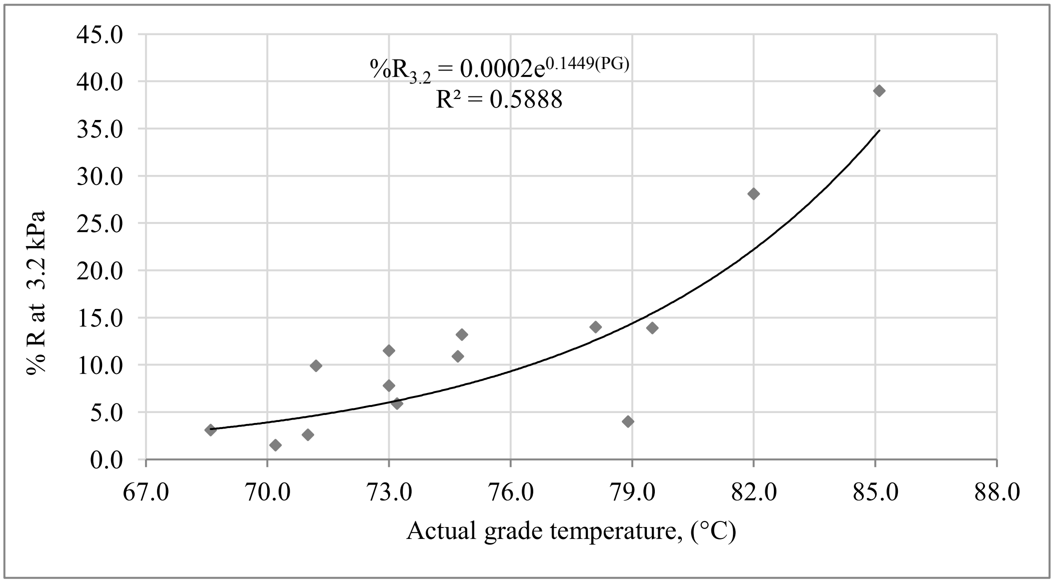

Figure C. 7. Percent recovery at 3.2 kPa per each passing temperature for Jeddah asphalts.

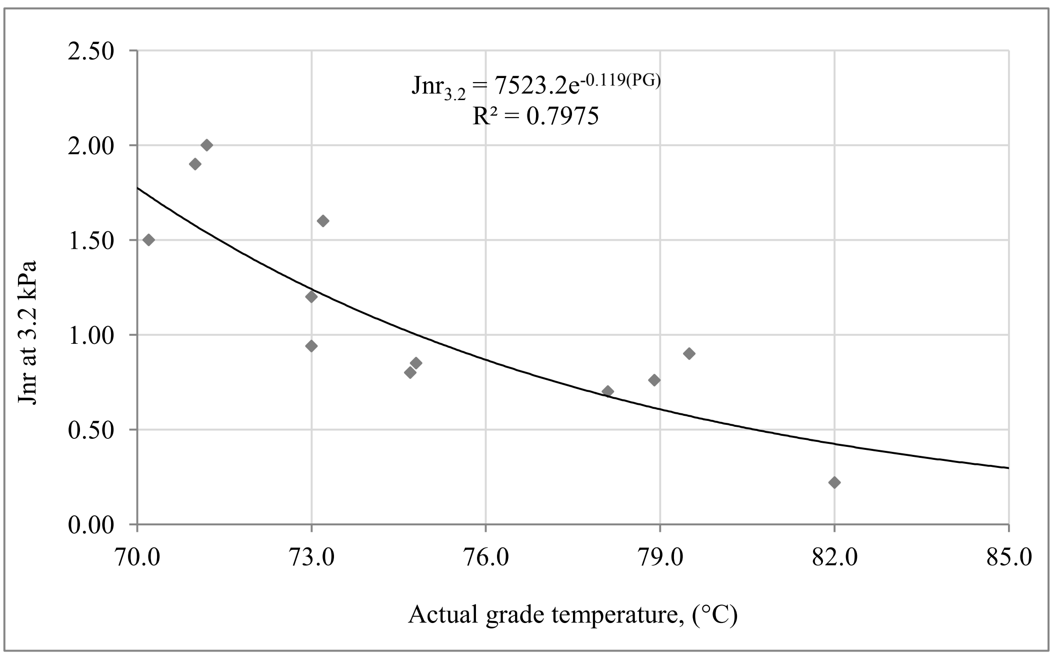

Figure C. 8. Jnr at 3.2 kPa per each passing temperature for Jeddah asphalts.

Table C. 3. MSCR results for Yanbu modified asphalts

Additive Name	**Actual Upper pass. Temp.**	**True PG**	**MSCR at 64°C**			
			100 Pa		**3200 Pa**	
			% $R_{0.1}$	**Jnr $_{0.1}$ (Kpa^{-1})**	**% $R_{3.2}$**	**Jnr $_{3.2}$ (Kpa^{-1})**
None	63.2	PG 58	0.0	0.00	0.0	0.0
SBS	72.1	PG 70	22	1.75	5.5	1.3
	82.8	PG 82	42	0.05	60.0	0.68
Pb 101	70.7	PG 70	25	1.7	1.0	1.80
	78.3	PG 76	30	0.15	15.0	0.70
Titan 7686	70.2	PG 70	20	1.6	1.5	1.75
	76.3	PG 76	45	1.1	18	1.10
	82.4	PG 82	70	0.44	33	0.72
Titan 7205	72.1	PG 70	25	1.4	7.0	1.40
	77.9	PG 76	45	1.2	23	0.95
	83.3	PG 82	48	0.35	35	0.44
SBS: Titan 7686	75.3	PG 70	20	1.1	20	1.30
	75.9	PG 76	35	1.2	24	1.20
	77.5	PG 76	40	0.23	28	0.83
SBS:Titan 7205	73.9	PG 70	20	1.35	12	1.40
	78.4	PG 76	55	0.37	17	0.90
	80.4	PG 76	80	0.13	45	0.65

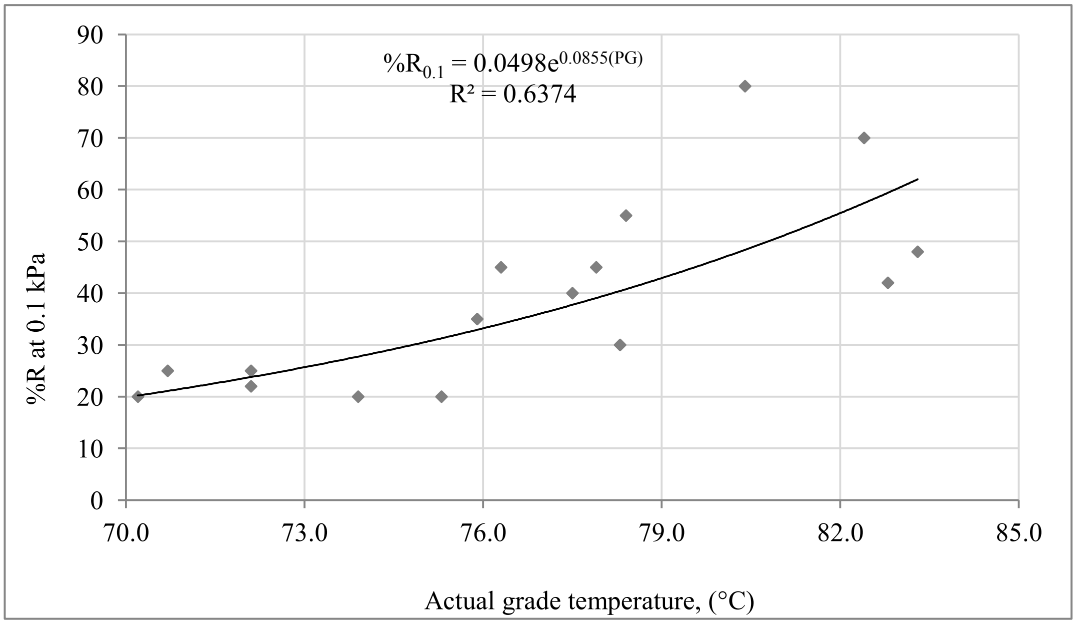

Figure C. 9. Percent recovery at 0.1 kPa per each passing temperature for Yanbu asphalts.

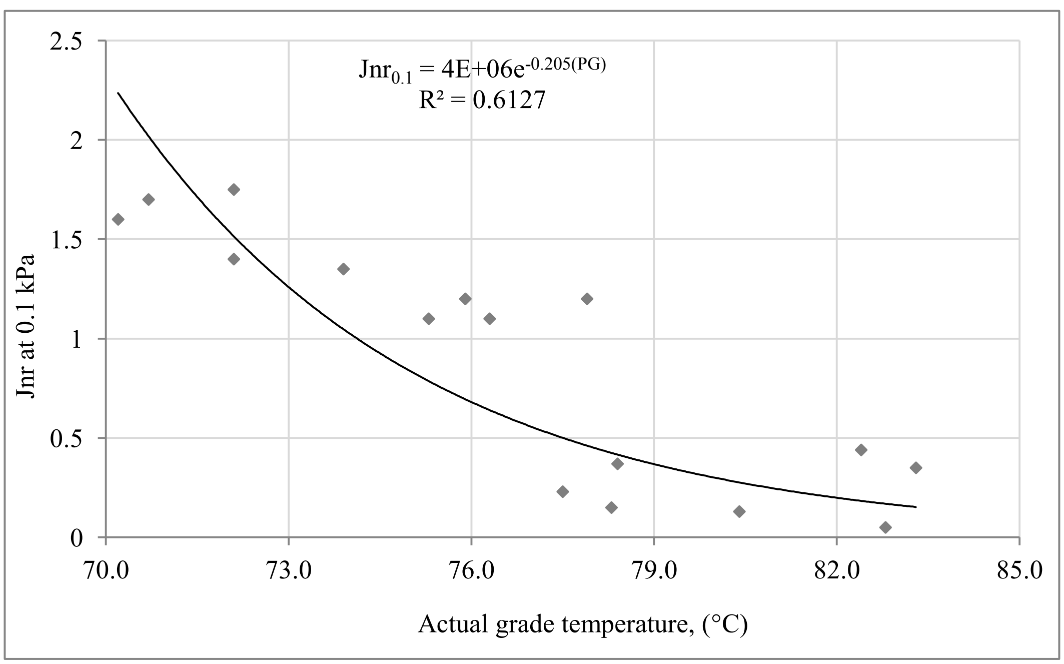

Figure C. 10. Percent recovery at 0.1 kPa per each passing temperature for Yanbu asphalts.

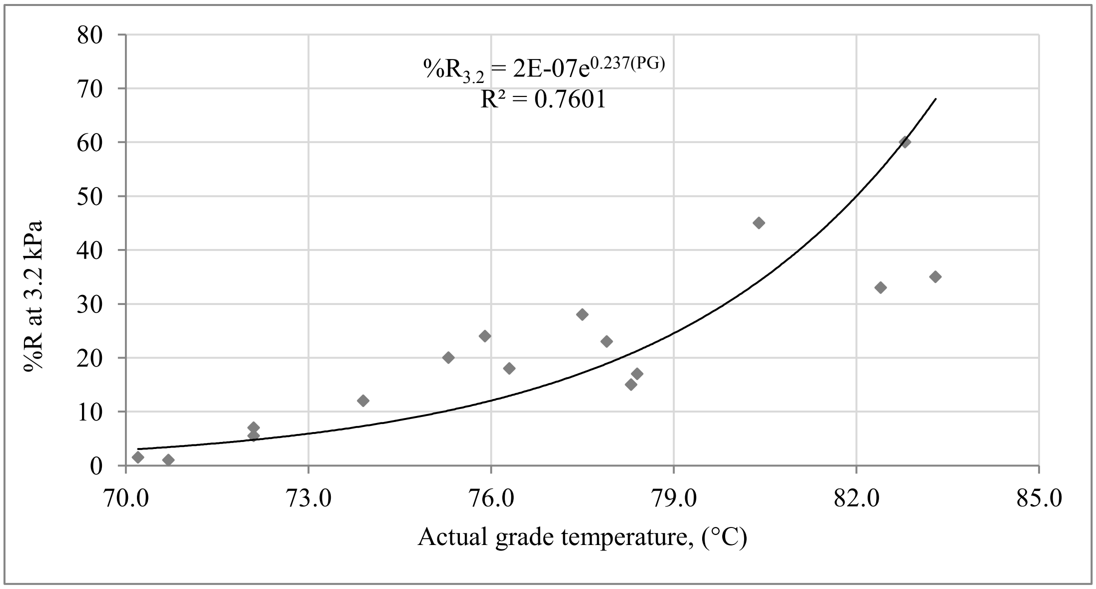

Figure C. 11. Percent recovery at 3.2 kPa per each passing temperature for Yanbu asphalts.

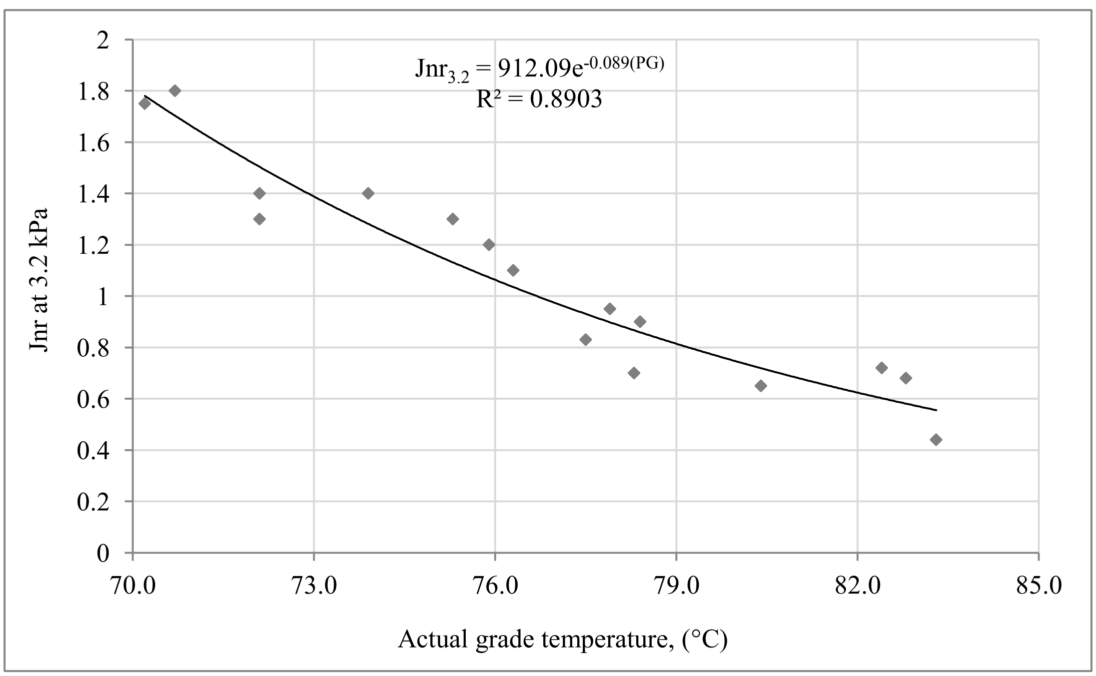

Figure C. 12. Jnr at 3.2 kPa per each passing temperature for Yanbu asphalts.

Vitae

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Academic Career

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